CAPACITATED ARC ROUTING PROBLEMS IN OPENING ACCESS BY DEBRIS COLLECTION OPERATION IN DISASTERS(Dissertation_全文)

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Preface

This doctoral dissertation consists of the research effort and results of the following journal and conference papers.

Journal Papers

- Pramudita, A., Taniguchi, E., and Qureshi, A.G., Model of Debris Collection Operation after Disasters and Its Application, European Journal of Operational Research, 2013. (*Submitted*)
- Pramudita, A., Taniguchi, E., and Qureshi, A.G., Undirected Capacitated Arc Routing Problem in Debris Collection Operation After Disasters, Journal of Japan Society of Civil Engineers, Ser. D3 (Infrastructure Planning and Management), Vol.68, No.5, pp.805-814, 2012.

Peer-Reviewed Conference Proceedings

- Pramudita, A., Taniguchi, E., and Qureshi, A.G., Location and Routing Problem of Debris Collection Operation After Disasters with Realistic Case Study, the 8^{th} International Conference on City Logistics, June, 2013.
- Pramudita, A., Taniguchi, E., and Qureshi, A.G., Location-Capacitated Arc Routing Problem in Debris Collection Operation After Disasters, Proceedings of the 4^{th} International Conference on Transportation and Logistics, CD-ROM, August, 2012.
- Pramudita, A., Taniguchi, E., and Qureshi, A.G., Undirected Capacitated Arc Routing Problem in Debris Collection Operation After Disasters, Proceedings of Infrastructure Planning and Management Conference Vol.44, CD-ROM, November, 2011.

Conference Papers

- Pramudita, A., Taniguchi, E., and Qureshi, A.G., Application of Debris Collection Operation after Disasters Model - Case Study: Tokyo Metropolitan Area Hazard Maps, International Seminar on Humanitarian Logistics and Emergency Management, November, 2012.
- Pramudita, A., Taniguchi, E., and Qureshi, A.G., Research Symposium on Humanitarian Logistics and Emergency Management, February, 2012.

Abstract

CAPACITATED ARC ROUTING PROBLEMS IN OPENING ACCESS
BY DEBRIS COLLECTION OPERATION IN DISASTERS

by

ANDIE PRAMUDITA SAIDHIDAYAT

Doctor of Engineering in

Kyoto University

Management of debris is a concern after any major disaster. In particular, debris removal after a disaster presents challenges unique to that disaster. Often, the debris removal process takes months or even years to finish. It is likely to be a concern for some time to come since there exists many factors that make it such a costly and complex operation. The cost is mostly arising from the cost of collection and transportation to the disposal sites. The transportation routing problem will be the subject of this study. The debris collection operation after disasters is a new Capacitated Arc Routing Problem (CARP). The uniqueness of this problem is due to the limited access from one section to the other, as a result of the blocked access by debris. Therefore a new constraint, which is developed in this study as access possibility constraint was added to the classical CARP. A tabu search meta-heuristics is also proposed to solve the augmented CARP formulation for the debris collection operation problem. Case studies on a test network as well as on realistic instances based on estimates of debris due to likely large scale natural disaster in Tokyo Metropolitan Area have also been reported at the end under various scenarios such as with or without multiple intermediate depots and single vs. multiple vehicles (groups) operation.

In a brief manner, we summarize every chapter in this dissertation as follows. Chapter 1 of this thesis explains the background of the research, motivations and objectives of the research, methods of the research and contributions of the research objectives. In this chapter we explain our motivation to conduct this research, the results and findings, as well as the novelty of our research. Final section of the chapter describes the structure of thesis.

Chapter 2 describes basic concepts and theories related to the research topic. We conduct literature review of works of researchers that mainly from the theoretical views of

disaster and emergency management and literature related to disaster waste management. We emphasized literature related to a historical perspective on routing problem in the disaster waste management since it is closely related to our research about disaster debris collection operation routing problem. Further we investigate papers methodology related to our research topic.

Chapter 3 explains the process of developing the mathematical model. A mathematical model is a description of a system using mathematical concepts and language. First, based on the previous chapters in where the methodologies explained, we developed the basic framework of the model. As a basic idea in the mathematical model of disaster debris collection operation is that the new model proposed in this research is a modification of the classical model of Capacitated Arc Routing Problem (CARP). A modification in classical CARP is therefore, required to solve this kind of problem i.e., by adding a new constraint, which is mentioned in this research as access possibility constraint.

Further, a tabu search meta-heuristics is proposed to solve the problem, as tabu search or heuristics in general are practically more appropriate and faster to solve large instances. Final section of the chapter describes the benchmarking problem. In order to assess the accuracy of the tabu search algorithm more conclusively, we performed a computational experiment on a set of benchmark problems and compared the result with best known solutions for the 25, 50 and 100 customer instances of Solomon's Vehicle Routing Problem with Time Windows (VRPTW) benchmark problems (Solomon, 1987).

Chapter 4 describes the research hypothesis testing. A research hypothesis is the statement created by researchers when they speculate upon the outcome of a research or experiment. Before applying the formulation of the disaster debris collection problem (i.e., its underlying modified CVRP) on the realistic case study of Tokyo Metropolitan Area, the model formulation is tested on a small problem instance. The hypothetical test instance is performed into four scenarios i.e., (i) single intermediate depot and single vehicle; (ii) multi intermediate depots and single vehicle; (iii) multi intermediate depots and multi vehicles; and (iv) the best location of intermediate depot.

Chapter 5 explains the model application of the disaster debris collection problem in solving the realistic case study. An estimation procedure was established by Hirayama et al. (2010) to assess the amount of debris resulting from earthquake and flood disasters in Tokyo Metropolitan Area. In that case study, the amount of debris from earthquake and catastrophic flood disasters in Tokyo Metropolitan Area was estimated according to the hazard maps.

Considering the large size of entire Tokyo Metropolitan Area, the model formulation will be tested in two spot locations only, representing eastern and western part of Tokyo. Location factor of disposal sites or intermediate depots is the main issue that should be taken into account in performing cost optimization. Therefore, the optimization process determines optimum number of intermediate depot established the best location and minimum capacity of each.

Chapter 6 concludes our research and proposes future research topics.

To my parents, my wife Lena and my child Gavin Adaino.

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Acknowledgments

Every research is dealing with cooperation process among players. This dissertation is only one of example of cooperative outcomes of one Doctoral student with his/her supervisors. Sharing idea, discussion, and guidance and giving constructive, sometimes very though comments and questions, all of them could be considered as cooperative processes and in its time will lead the research to its ultimate goals. During my three years tenure in doctoral courses at Kyoto University, this acknowledgement is the chance to express my appreciation to all the players involved in making this dissertation possible.

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Symbols and Abbreviations

ADB	Asian Development Bank
ARP	Arc Routing Problem
CARP	Capacitated Arc Routing Problem
CPP	Chinese Postman Problem
CVRP	Capacitated Vehicle Routing Problem
EUROMA	European Operations Management Association
FEMA	Federal Emergency Management Agency
IFRC	International Federation of Red Cross and Red Crescent Societies
INFORMS	Institute for Operations Research and the Management Sciences
INSEAD	*Institut Européen d'Administration des Affaires*
LRP	Location Routing Problem
MIP	Mixed Integer Programming
NP	Non-deterministic Polynomial-time
OM	Operations Math
OR	Operations Research
POMS	Production and Operation Management Society
RPP	Rural Postman Problem
TSP	Traveling Salesman Problem
UNEP	United Nations Environment Programme
UNISDR	United Nation Office of Disaster Risk Reduction
VRP	Vehicle Routing Problem
VRPTW	Vehicle Routing Problem Time Windows
WHO	World Health Organization

Chapter 1

Introduction

1.1 Backgrounds

Disaster was defined in UNISDR (2009) as a serious disruption of the functioning of a community or a society, involving widespread human, material, economic or environmental impacts, which exceed the ability of the affected community or society to cope using its own resources. Disaster impacts may include loss of life, injury, disease and other negative effects on human physical, mental and social well-being, together with damage to property, destruction of assets, loss of services, social and economic disruption and environmental degradation.

In an effort to minimize the impact of disasters, disaster and emergency management is urgently needed. The disaster and emergency management was defined in IFRC (2010) as the organization and management of resources and responsibilities for dealing with all humanitarian aspects of emergencies, in particular preparedness, response and recovery in order to lessen the impact of disasters.

Logistics is one of the fundamental aspects in implementing the disaster management. A branch of logistics which specializes in organizing the delivery and warehousing of supplies during natural disasters or complex emergencies to the affected area and people is recognized as humanitarian logistics. The humanitarian logistics was defined by Thomas and Mizushima (2005) as the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials, as well as related information from the point of origin to the point of consumption for the purpose of meeting the end beneficiary's requirements.

In related to the routing problem in disaster management issues, a vast literature exists were studying about evacuation and relief distribution topic. Some of the literature are Wohlgemuth et al. (2012) which evaluated the benefits of dynamic optimization anticipating varying travel times (i.e., the availability of connections in this case) as well as unknown orders (i.e., the integration of demand regions on short notice) in the specific environment of emergencies; Sheu (2007) presented a hybrid fuzzy clustering-optimization approach to the operation of emergency logistics co-distribution responding to the urgent relief demands in the crucial rescue period; Yi and Kumar (2007) presented a meta-heuristic of ant colony optimization for solving the logistics problem arising in disaster relief activities; Yi and Odzamar (2007) described an integrated location-distribution model for coordinating logistics support and evacuation operations in disaster response activities; and many others.

In addition to such studies mentioned above, an important topic related to disaster management, which has not much been researched, is about disaster debris collection operation. All natural disasters whether they involve earthquake, tsunami, flood, landslide or other natural hazards always result in disaster debris. Disaster debris is also termed as disaster-generated waste in FEMA (2007), which was defined as any material, including trees, branches, personal property and building material on public or private property that was directly deposited by the disaster. Increasingly, the management of debris generated by natural disasters is becoming a major expenditure in the immediate aftermath and longer-term recovery effort. Debris generated in some large-scale disasters can be equivalent in volume to years of normal solid waste production in the affected areas.

In this research, disasters are assumed as big disasters or catastrophes which remain large scale of debris scattered on almost whole affected area including on the exits road. Meanwhile, the disaster debris collection operation can be considered as an operation to remove the debris which blocks road in order to rebuild access connectivity. The access connectivity is highly impacts on humanitarian relief distribution process. In case of debris blocked road and disrupt the access connectivity, the humanitarian relief distribution would experience deceleration.

Therefore management of debris is a concern after any major disaster. In particular debris removal after a disaster presents challenges unique to that disaster. Often, the debris removal process takes months or even years to finish. As an illustration to be able to imagine how large the amounts of debris, Luther (2008) reported that a total of about 113.5 million cubic yards of debris was left-over in Alabama, Mississippi and Louisiana, as an aftermath of Hurricane Katrina; Federal Emergency Management Agency (FEMA) an estimated debris removal cost of over US$ 4 billion as federal funding. It is likely to be a concern for some time to come since there exists many factors that make it such a costly and complex operation. The cost is mostly arising from the cost of collection and transportation to the disposal sites. Technical factors which form the cost of this process are firstly limited space to establish appropriate temporary or final disposal sites. The second factor is the cost of providing necessary heavy vehicles and tools to execute the disaster debris collection operation. The third factor is the transportation cost of debris disposal that depends on vehicle's route choice to transport the debris to the temporary or final disposal sites.

Routing problem becomes one of the important issues in cost efficiency considering that route choice greatly affect total travel cost that is incurred in the disaster debris collection operation. As well as disposal site (termed as intermediate depot) issue, whereby determining of the number, the location and the capacity are considered very important due to affect the vehicle routing in the operation. The combination of disposal site location and vehicle routing problem is the subject of our research in the following. In the context of location and routing problem, the following research questions can arise: What is the correlation among location, routing and travel cost? How to formulate this kind of problem with appropriate mathematical models? How to solve such mathematical models? (i.e., which solution algorithm shall be used to obtain the optimum cost?)

1.2 Motivations and Objectives of the Research

Motivation of this research is to address these research questions above by developing new variant of the undirected Capacitated Arc Routing Problem (CARP). CARP itself is an underlying of the problem exists in our research. Moreover, the research topic has some uniqueness, including the blocked accesses problem (discussed more in the next section) and so far not much research has been done in this direction.

The problem in this research is motivated from disaster debris collection operation; for that a modification in classical CARP is required. In this new CARP variant, roads are treated as a set of arcs. A set of required arcs consists of arcs that are covered by debris, thus they have demands to service. The objective function of the CARP is to service all required arcs in the graph at least cost with feasible vehicle routes. The modification of the classical CARP results in a disaster debris collection operation model which has objective to minimize the operational cost through optimization of vehicle routing and disposal site location.

Objectives of the research are: (i) to enhance and to enrich the topic of research in humanitarian logistics more on the topic of disaster debris removal (collection) operation; (ii) to modify classical CARP into disaster debris collection operation problem by adding new constraint i.e., access possibility constraint (which is classified into the family of dynamic constraint); (iii) to apply the resulting model formulation for solving artificial small problem instances using tabu search meta-heuristics; and (iv) to apply the resulting model formulation for solving a realistic case study, in order to evaluate the compatibility of the model with the real case problems.

1.3 Methods of the Research

In the debris collection problems, the sequences in visiting and servicing arcs are very important, because one section may block other sections. Initially, only adjacent arcs can be connected with each other, while for distant arcs there may be no way to be connected before removing the blocked access first. Another matter that should be paid attention to is that routes also can only be operated in a particular sequence, considering that one completed route will affect the access possibility for the other routes. This constraint is developed in this study as a binary matrix termed as the access possibility matrix, where an entry is equal to 1 if a vehicle can possibly move from one arc to another; 0 otherwise. To better understand the problem, let's see problem illustrations in **Figure 1.1**. At stage 1, the access possibility from 0 to 1 is equal to 1 (i.e.,p_{01}=1); and p_{02}=0 because the access is still blocked. In stage 2 after arc no.1 has been serviced, p_{02}becomes 1. It means that vehicle should service arc no.1 first, before being allowed to service arc no.2 through the shortest path. The access possibility from one point to the others always changes every time a single arc has been serviced by a vehicle.

Similar to the various CARP-related researches (discussed in details in next chapter) the underlying CARP to our disaster debris collection operation in this research is transformed into the Capacitated Vehicle Routing Problem (CVRP). Both the CARP and the CVRP are in fact closely related, the main difference being that in the CARP customers are set of arcs while in the CVRP customers are set of nodes.

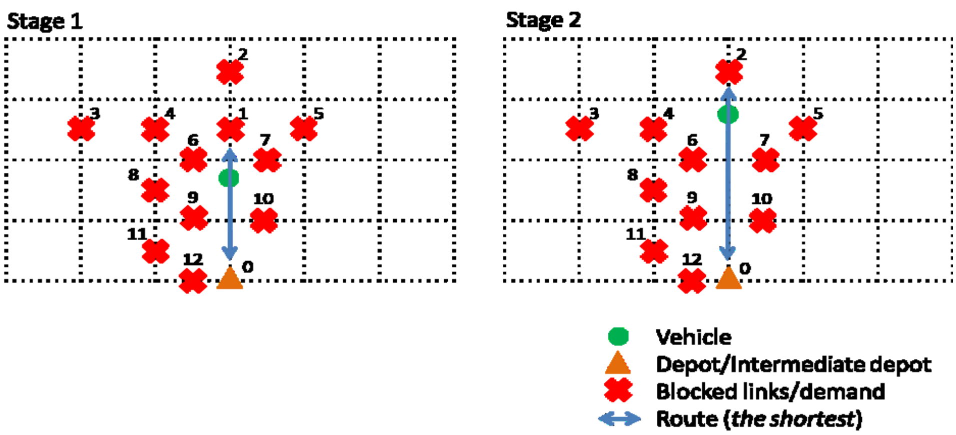

Figure 1.1 Problem illustrations

The resulting model formulation is applied to solve a realistic problem based on disasters debris estimation data resulting from large scale earthquake and flood disasters scenarios in Tokyo Metropolitan Area by Hirayama et al. (2010). In this study, an estimation procedure was established to assess the amount of debris resulting from earthquake and flood disasters. Per unit generation of earthquake disaster debris was examined on the basis of observed debris discharge from the 1995 Great Hanshin Awaji Earthquake and the 2004 Niigata Chuetsu Earthquake. The estimation disaster debris per unit generation from the 1995 Great Hanshin-Awaji Earthquake was reported in Hyogo Prefecture, Earthquake Disaster Debris Operation (1997) as 81.9 ton/house. In the Mid Niigata Earthquake, per unit generation of disaster debris caused by demolition and construction of housing was reported in Kanto District Office, Ministry of the Environment Government of Japan (2006) as 57 ton/house to 85 ton/house. In addition to that spatial and statistical data of Tokyo Metropolitan Area is also used based on Japanese Standard Grid Square and Grid Square Code used for the Statistics (Announcement No.143 by the Administrative Management Agency Japan, on July, 12, 1973).

1.4 Contributions of the Research

Contributions of the research is enhancing innovation scientific related to the location and routing problem, particularly in disasters issues. Therefore to show the novelty of disaster debris collection operation in this research, let us compare it with the snow removal operation problem in Tagmouti et al. (2007), which is similar with our problem. The fundamental difference between disaster debris collection operation and snow removal operation is described as follows. In snow removal operation, the timing of the intervention is of prime importance. That is, if the intervention is too early or too late, the cost in material and time sharply increases. On the other hand, in disaster debris collection operation, because some accesses are blocked by the debris, sequence in visiting and servicing arcs at the previous road network structure affect aggregate accessibility at the next one. Besides studied by Tagmouti et al. (2007), many important publications of the past ten years related to the snow removal operation problem which is similar with our problem, have been well reviewed by Aguilar et al. (2012).

As an important and new point here, the uniqueness of this kind of CARP problem is due to the limited access from one section to the others, as a result of the blocked access by debris. A modification in classical CARP is therefore, required to solve this kind of problem i.e., by adding a new constraint, which is mentioned in this study as access possibility constraint. This constraint sets whether a vehicle can possibly move from one node to another in a particular network, or not.

1.5 Structure of the Thesis

The remaining thesis structure is organized as follows. The literature review is first introduced in Chapter 2. Then, the model of disaster debris collection operation is presented in Chapter 3. The hypothesis testing is presented in Chapter 4. The application on a realistic case study of Tokyo metropolitan area is presented in Chapter 5. Finally, the conclusions and future research follows in Chapter 6. To better understand the flow of this research let's see the flow chart in **Figure 1.2**.

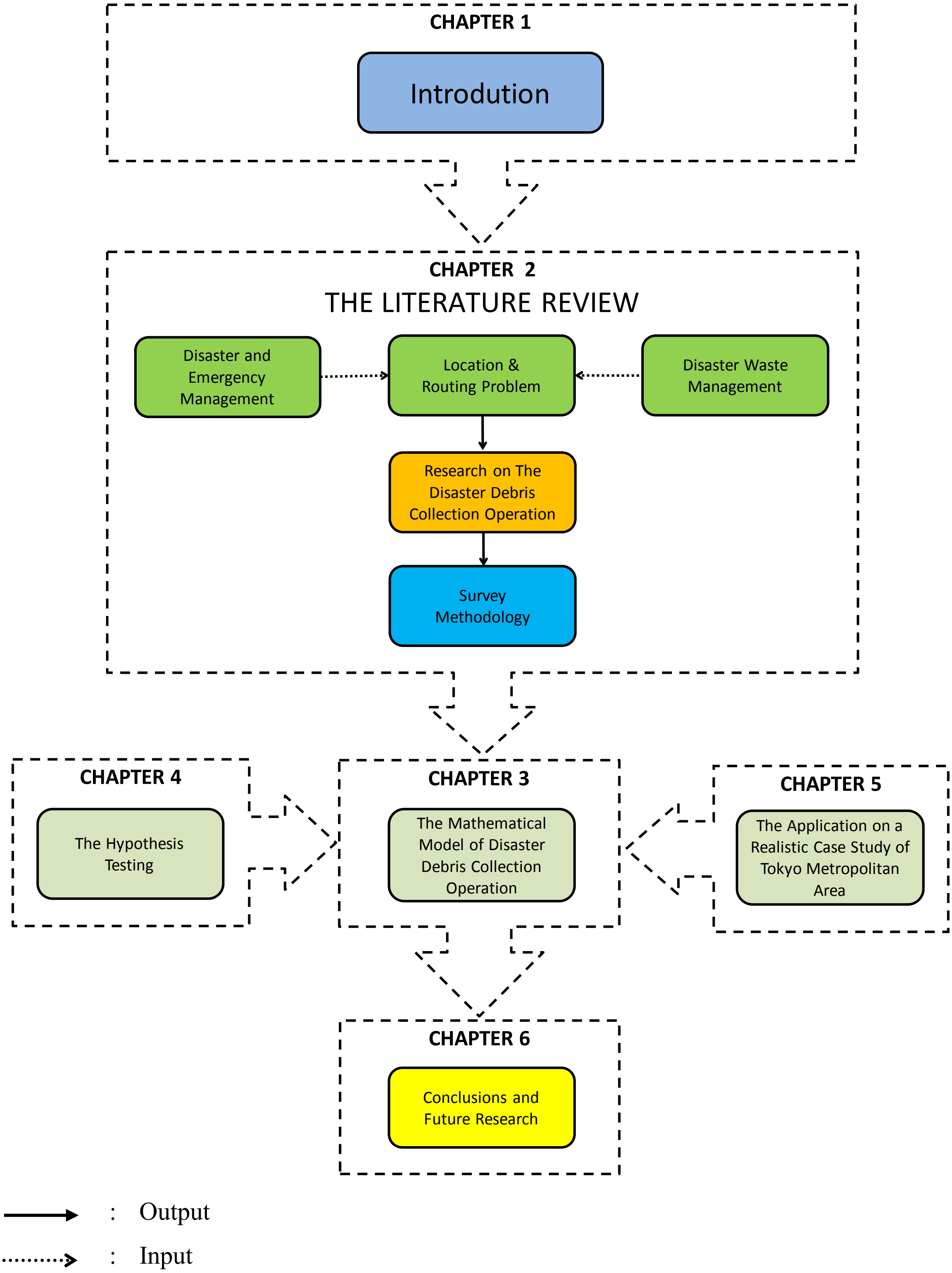

Figure 1.2 Flow chart of the thesis structure

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Chapter 2

The Literature Review

2.1 Introduction

As also explained in the previous chapter, disasters was defined in UNISDR (2009) as a serious disruption of the functioning of a community or a society, involving widespread human, material, economic or environmental impacts, which exceed the ability of the affected community or society to cope using its own resources. Disasters can occur as a consequence of the impact of a natural or a human-caused hazard. Natural hazards comprise phenomenon directly caused by the nature, meanwhile human-caused hazards may be intentional, such as the illegal discharge of oil, or accidental such as toxic spills or nuclear meltdown.

There are four main types of disasters: (i) Natural disasters include floods, hurricanes, earthquakes and volcano eruptions that can have immediate impacts on human health, as well as secondary impacts causing further death and suffering from floods causing landslides, earthquakes resulting in fires, tsunamis causing widespread flooding and typhoons sinking ferries; (ii) Environmental emergencies include technological or industrial accidents, usually involving hazardous material, and occur where these materials are produced, used or transported; (iii) Complex emergencies involve a break-down of authority, looting and attacks on strategic installations, conflict situations and war; (iv) Pandemic emergencies involve a sudden onset of a contagious disease that affects health but also disrupts services and businesses, bringing economic and social costs.

There is no area that is immune from disaster, though vulnerability to disaster varies. As a representation case, Asia is the world's most disaster-prone region, and Asia's poor, lacking in resources and more vulnerable and exposed to the elements, have borne the brunt of the region's cataclysms. Natural disasters can strike anywhere, however Asia's poor and those living in poor countries with weak governance and economies get hit the most.

ADB (2011) reported more than 2,200 natural disasters struck Asia in the past 20 years, claiming close to one million lives, with the following six mega-disasters accounting for three-quarters of fatalities: Bangladesh’s cyclone Gorky in 1991 (140,000 deaths), the

2004 Indian Ocean tsunami (more than 200,000 deaths), Pakistan's 2005 earthquake (75,000 deaths), Myanmar's 2008 cyclone Nargis (140,000 deaths), China's 2008 earthquake (90,000 deaths) and Japan's 2011 earthquake and tsunami (over 200,000 deaths), and so on.

IFRC (2009) reported about the deadly math that 40% of the world's natural disasters occurred in Asia from 1999 through 2008, the continent accounted for 82% of disaster deaths, as shown in **Figure 2.1** and **2.2**. As well as from 1999 to 2008 about 1,501 natural disasters killed more than 975,000 people, almost half the deaths resulted from earthquakes and tsunamis. The disaster types and deaths they cause can be seen in **Figure 2.3**, **2.4** and **2.5**.

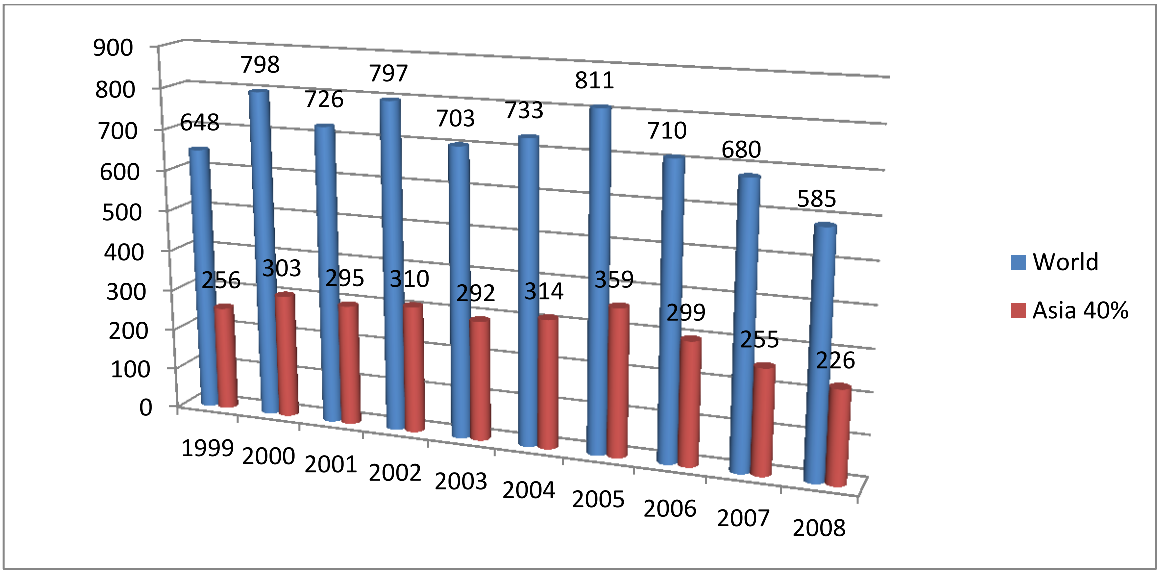


Figure 2.1 Numbers of disasters

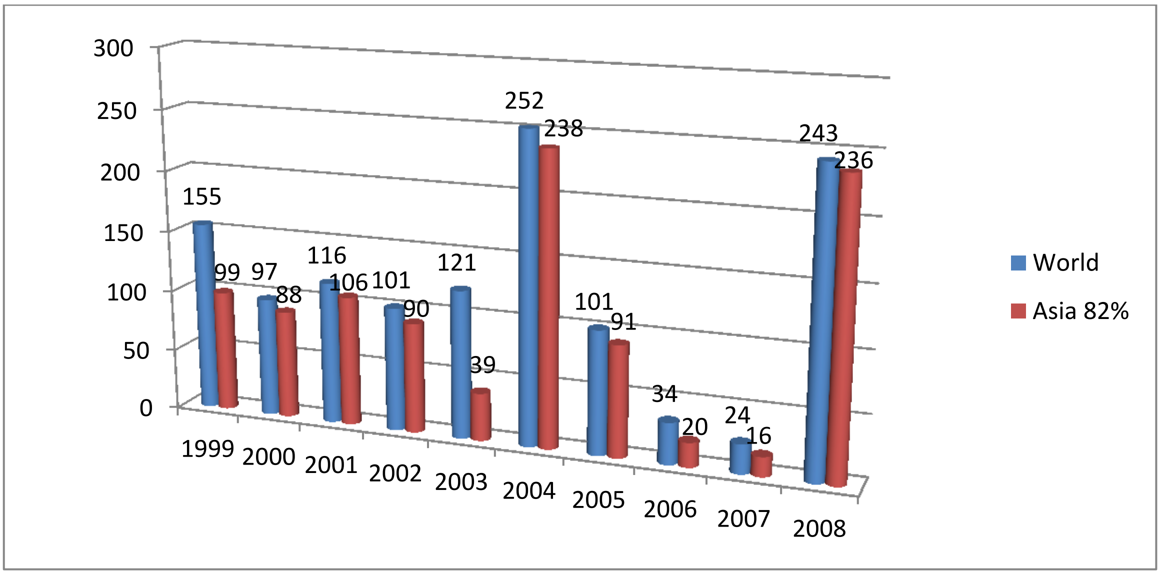


Figure 2.2 Disaster deaths

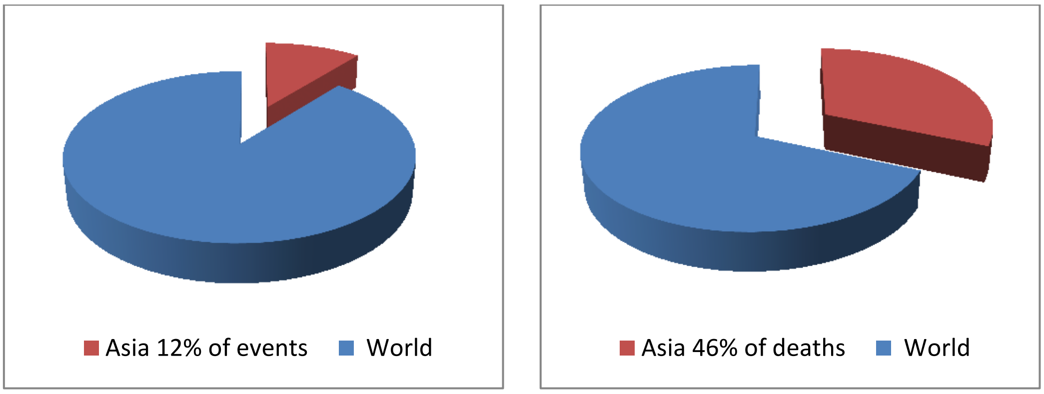


Figure 2.3 Earthquakes and tsunamis

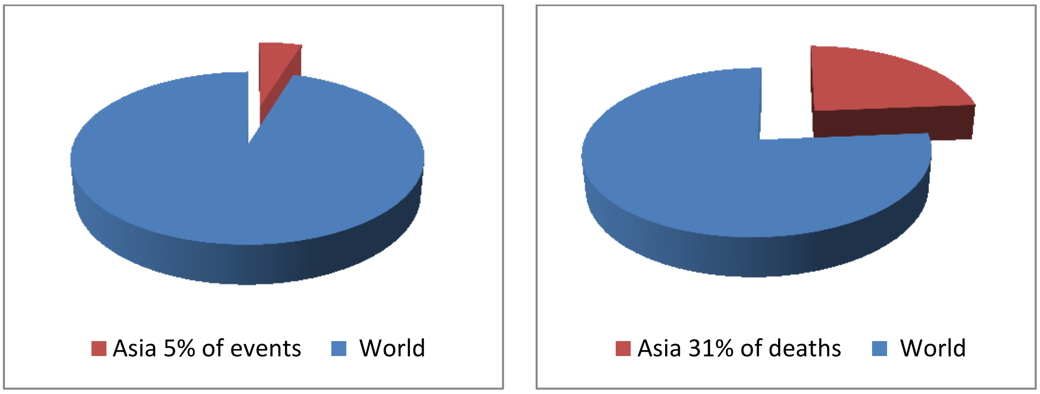


Figure 2.4 Droughts and food insecurities

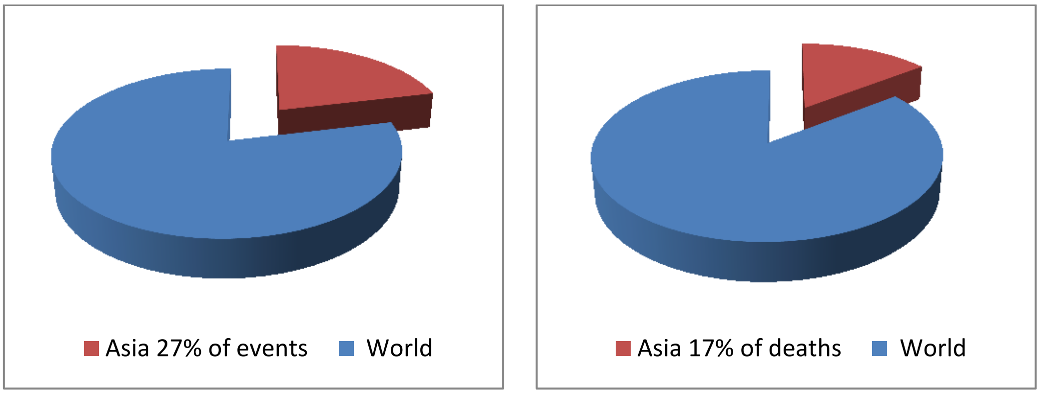


Figure 2.5 Windstorms

2.2 Disaster and Emergency Management

The purposes of this section are to review historical trends, to define objective and to define phases of disaster and emergency management.

2.2.1 Review of Historical Trends

FEMA (2007) reported that the concerning and legislation of disaster and emergency management was starting from the Congressional Act of 1803. It provided one New Hampshire town with assistance after an extensive fire. In the century that followed, ad hoc legislation was passed more than a hundred times in response to hurricanes, earthquakes, floods and other disaster.

In the 1930s, when the federal approach to problems became popular, the Reconstruction Corporation was given authority to make disaster loans for repair and reconstruction of certain public facilities following an earthquake, and later, other types of disasters.

In 1934, the Bureau of Public Road was given authority to provide funding for highways and bridges damaged by natural disasters. The Flood Control Act in 1936 created the National Flood Program. It established a federal responsibility to assist in flooding mitigation programs along the Mississippi River and other major rivers. During the 1940s, Civil Defense programs, such as air raid warning and emergency shelter systems were established to protect the civilian population.

The Disaster Relief Act of 1950 gave the president authority to issue disaster declarations, authorizing federal agencies to provide direct assistance to state and local governments. The Federal Civil Defense Act of 1950 created a nationwide system of civil defense agencies, and defense drill became routine in schools, government agencies and other organizations. The Federal Civil Defense Act was amended to include state government responsibility.

Massive disaster during the 1960s and 1970s required major federal response and recovery operations by the Federal Disaster Assistance Administration, which was a division established within the Department of Housing and Urban Development. Hurricane Carla in 1962, Hurricane Betsy in 1965, Hurricane Camille in 1969, Hurricane Agnes in 1972, the Alaska Earthquake in 1964 and the Southern California Earthquake in 1971 all served to focus attention on the issue of natural disasters and brought about increased legislation. The Disaster Relief Act in 1969 created a federal coordinating officer to represent the president in the relief effort. Extended in 1974, the Act authorized individual and family assistance through state and local government.

In 1978, the National Governor’s Association sought to decrease the number of agencies with whom state and local governments were forced to work. They asked President

Jimmy Carter to centralize federal emergency functions. President Carter's 1979 executive order merged many of the separate disaster-related responsibilities into a new FEMA. Among other agencies, FEMA absorbed: the Federal Insurance Administration, the National Fire Prevention and Control Administration, the National Weather Service Community Preparedness Program, the Federal Preparedness Agency of the General Services Administration and the Federal Disaster Assistance Administration activities from Department of Housing and Urban Development. Civil defense responsibilities were also transferred to the new agency from the Defense Department's Civil Preparedness Agency.

In March 2003, FEMA along with twenty two other agencies, programs and office became the Department of Homeland Security. This new department, headed by Secretary Tom Ridge, brought a coordinated approach to national security from emergencies and disaster both natural and man-made. In New Jersey, Emergency Management falls under the direction of the New Jersey State Police. The state is divided into three regions, North, Central and South. Each county is assigned a representative from the State Police. Warren County is in the North region. Each municipality, by law, must appoint an Emergency Management Coordinator and a Local Emergency Planning Council. Every Coordinator is responsible for writing and maintaining an all hazards emergency operations plan.

2.2.2 The Objectives

Disaster and emergency management refers to the policies, programs, administrative actions and operations undertaken to address a natural or man-made disaster through preparedness, mitigation, response and recovery. Although the actions taken to address a specific disaster vary depending on the hazard, four objectives of disaster management by Lindell et al. (2007) applied to every situation as follows: (i) <u>Reduce damages and deaths</u>. Effective disaster management reduces or avoids morbidity, mortality, and economic and physical damages from a hazard. The methods used to achieve this include hazard and vulnerability analysis, preparedness, mitigation and prevention measures, and the use of predictive and warning systems; (ii) <u>Reduce personal suffering</u>. Disaster management reduces personal suffering, such as morbidity and emotional stress following a hazard. The methods used to prevent suffering include hazard and vulnerability analysis, preparedness, and mitigation and prevention measures; (iii) <u>Speed recovery</u>. The methods to accomplish this objective include effective response mechanisms and the institution of recovery programs and assistance; (iv) <u>Protect victims</u>. Disaster management provides protection to victims and/or displaced persons. Facilities utilize preparedness, response mechanisms, recovery programs and assistance to address shelter needs and provide protective services.

2.2.3 The Phases

Current thinking defines four phases of disaster and emergency management i.e., mitigation, preparedness, response and recovery phase. The mitigation and preparedness phases occur as disaster and emergency management improvements are made in anticipation of a disaster event. Disasters occur between preparedness and response phase. Such phases was illustrated by WHO (2002) as a cycle as shown in **Figure 2.6**.

(a) Mitigation

Mitigation is activities that providing a critical foundation in the effort to reduce the loss of life and property from natural and/or manmade disasters by avoiding or lessening the impact of a disaster and providing value to the public by creating safer communities. Mitigation seeks to fix the cycle of disaster damage, reconstruction and repeated damage. These activities or actions, in most cases, will have a long-term sustained effect.

Figure 2.6 Disaster and emergency management cycle

(b) Preparedness

Preparedness is a continuous cycle of planning, organizing, training, equipping, exercising, evaluating and taking corrective action in an effort to ensure effective coordination during incident response. Within the National Incident Management System, preparedness focuses on the following elements: planning; procedures and protocols; training and exercises; personnel qualification and certification; and equipment certification.

(c) Response

Response is activities that address the short-term direct effects of an incident, includes immediate actions to save lives, protect property and meet basic human needs. Response also includes the execution of emergency operations plans and of mitigation activities designed to limit the loss of life, personal injury, property damage, and other unfavorable outcomes. As indicated by the situation, response activities include applying intelligence and other information to lessen the effects or consequences of an incident; increased security operations; continuing investigations into nature and source of the threat; ongoing public health and agricultural surveillance and testing processes; immunizations, isolation, or quarantine; and specific law enforcement operations aimed at preempting, interdicting, or disrupting illegal activity, and apprehending actual perpetrators and bringing them to justice.

(d) Recovery

Recovery is the development, coordination, and execution of service and site-restoration plans; the reconstitution of government operations and services; individual, private-sector, nongovernmental, and public assistance programs to provide housing and to promote restoration; long-term care and treatment of affected persons; additional measures for social, political, environmental, and economic restoration; evaluation of the incident to identify lessons learned; post incident reporting; and development of initiatives to mitigate the effects of future incidents.

2.2.4 Humanitarian Logistics

The basic task of a logistics system is to deliver the appropriate supplies, in good condition, in the quantities required, and at the places and time they are needed, therefore logistics plays a critical role in disaster and emergency management. A branch of logistics which specializes in organizing the delivery and warehousing of supplies during natural disasters or complex emergencies to the affected area and people is recognized as humanitarian logistics. The humanitarian logistics was defined by Thomas and Mizushima (2005) as the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials as well as related information, from the point of origin to the point of consumption for the purpose of meeting the end beneficiary's requirements.

The term of humanitarian logistics, seems to have gained currency both in academia and in practice after the Indian Ocean Tsunami in 2004. The impact of the tsunami was so devastating claiming the lives of over 200,000 people and leaving millions homeless and the media scrutiny so intense highlighting the problems in the relief operations that there were worldwide outcries for improved logistics in humanitarian relief operations.

In recent years, humanitarian logistics has gained increased visibility in operations management. A number of annual conferences (e.g., POMS, INFORMS, EUROMA) hosted either a track or invited sessions on humanitarian logistics, humanitarian operations, emergency response or some variation of the theme. In his plenary talk at INFORMS 2009, Hau Lee devoted a significant amount of time discussing current humanitarian research dealing with warehouse prepositioning, demand estimation and fleet management. At the 2009 Mini-Conference of the POMS College of Sustainable Operations, Luk Van Wassenhove illustrated the importance of humanitarian logistics research with examples from his work at INSEAD and discussed the need for more training to humanitarian logistics professionals. In addition, a number of journals (e.g., Interfaces, Supply Chain Forum, Operations Research Spectrum, among others) have hosted or are hosting special issues in humanitarian logistics. In particular, the "Interfaces" special issue on "Humanitarian Applications: Doing Good with Good OR" edited by Ergun et al. (2011), from Georgia Tech, highlights how OM models can have a real impact in the way organizations run their operations.

Through the description above can be concluded that one of the important role of logistics during the disaster response phase is on the humanitarian relief operation. The task of this operation includes getting the right product, to the right place, at the right time, takes on new meaning when roads, airports, bridges, and other logistics infrastructure are severely damaged or destroyed. The immediate spike in demand for food, water, clothing, and medical supplies is an order of magnitude greater than most supply chains are equipped to handle. In short, humanitarian relief is a unique and specialized type of supply chain and logistics problem. Relief logistics often need to be organized quickly under severe constraints. These include the pre-existing logistics infrastructure in the affected area, political factors, the damage caused by the disaster, and sometimes the security environment in operating areas. Another important role of logistics is on the debris removal (collection) operation which can be considered as an operation to remove the debris which blocks road in order to rebuild access connectivity. The access connectivity is highly impacts on humanitarian relief distribution process. In case of debris blocked road and disrupt the access connectivity, the humanitarian relief distribution would experience deceleration.

2.3 Disaster Waste Management

This section is concerned to explain concepts and challenges of disaster waste management as well as lesson learned of the Great East Japan Earthquake.

2.3.1 The Concepts

Disaster-generated waste was defined in FEMA (2007) as any material, including trees, branches, personal property and building material on public or private property that was directly deposited by the disaster. Disaster-generated waste could also be termed as debris. Depending on the context, however in this research, debris can refer to a number of different things as result of disaster. Disaster waste is a well-recognized threat to health, safety and the environment, and can also be a major impediment to post-disaster rescue operations. Experience shows that disaster waste is often managed in an ad hoc manner, however, and that substantial improvements can be made in future response efforts. Typical disaster waste issues and their impacts as well as hazard types and their waste characteristics can be seen in **Table 2.1** and **2.2**.

Table 2.1 Typical disaster waste issues and their impacts

Typical of Disaster Waste	Impacts
Uncollected building rubble from damaged buildings	Impeded access and constrained rehabilitation & reconstruction activities. Waste tends to attract more waste since the site is already considered a dumping site.
Dumping in inappropriate areas and/or proliferation of scattered dump sites.	Potential human health and injury risks from dump sites too close to settlements, especially from hazardous materials. Destruction of valuable and. Impacts on drinking water supplies and damage to valuable fisheries. Additional costs if waste must be moved later. Increase in disease vectors (flies, mosquitoes, rats, etc.). Risk of waste piles collapsing.

Typical of Disaster Waste	Impacts
	Risk of fires. Risk of cuts from sharp materials, including used syringes.
Collapse of municipal solid waste services, including possible loss of experienced waste managers.	Lack of collection service and uncontrolled dumping of waste.
Uncontrolled dumping of healthcare waste from hospitals and clinics.	Serious health risks to local populations including the spread of disease and infection, for example from used syringes; odor problems.
Asbestos sheet exposure in collapsed structures or in re-use of asbestos for reconstruction	Health risks associated with inhalation.

Table 2.2 Hazard types and their waste characteristics

Hazards Types	Characteristics
Earthquakes	Structures collapse 'in-situ', i.e., floor slabs collapse on top of each other, trapping waste within damaged buildings and structures. This can lead to challenges in sorting out hazardous waste (e.g., asbestos) from non-hazardous (e.g., general building rubble).Handling waste often requires heavy machinery, which communities may not be able to afford or have difficulty to access. Collapsed buildings may overlap across streets, making access difficult for the search and rescue and relief operations. Quantities of waste are high compared to other disaster types since all building contents normally become waste.
Flooding	Floods often lead to mass displacement, which in turn requires shelters and camps and leads to large volumes of household wastes. Initial damage depends on the structural integrity of infrastructure, while building contents are normally damaged extensively. Mold may be present and timber may have begun to rot. Buildings are typically stripped by owners and waste placed on roads for collection. Waste is often mixed with hazardous materials such as household cleaning products and electronic goods. Flooding may bring mud, clay and gravel into affected areas, making access difficult once the floodwater recedes. Removal may be required for relief and recovery operations. The mud, clay and gravel maybe mixed with hazardous materials, requiring further assessment before dumping.

Hazards Types	Characteristics
Tsunami	Strong tsunamis can cause widespread damage to infrastructure; spreading debris over large areas. Debris is often being mixed with soils, trees, bushes and other loose objects such as vehicles. This makes waste difficult to handle and segregate.
Hurricanes typhoons cyclones	Strong winds can tear the roof off buildings, after which walls may collapse. Poorly constructed houses and huts can "fold" under roof tops. Even brick and concrete walls may collapse. Waste is spread over open land, streets, and marketplaces. This would include roofing materials, small items and dust carried by the wind. This may cause serious problems where asbestos is present. Ships and boats are often thrown ashore and destroyed, requiring specialized waste management. Vessels that sink in harbors need to be removed. Electrical and telephone grids as well as transformers containing oil and PCBs may be destroyed.
Conflict short-term	Intense, short-term conflicts can involve rockets, missiles and bombs, which, combined with land combat, result in damage to buildings and infrastructure, key strategic installations being bombed and/or widespread damage to industrial and residential areas. Damaged infrastructure is often burnt, resulting in the destruction of most internal furnishings and fittings. This reduces the quantities of debris to be managed and leaves primarily non-flammable items such as concrete, bricks and stones. Bridges, roadways, railway structures etc. are often targeted. Their clearing requires heavy machinery such as excavators and bulldozers. Waste collection vehicles may be damaged or be commandeered for military purposes. Unexploded ordnance (UXO) including undetonated landmines may be present among waste.
Conflict protracted	Protracted conflicts share similarities with short-term, intense conflicts but there is often more widespread damage to building and infrastructure, and increased use of landmines on or near strategic roadways and facilities.

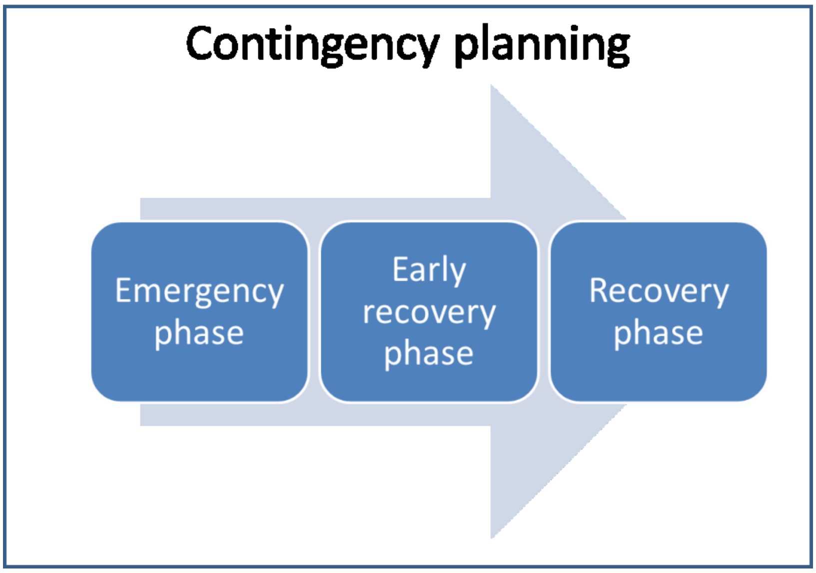


Figure 2.7 Disaster waste management phases

The descriptions about disaster waste above indicate the importance and urgency of a disaster waste management. Disaster waste management is the process which consists of: (i) Determining the appropriate response and recovery strategies to be implemented after a disaster (based on assessments of vulnerability); (ii) Identifying and agreeing responsibility for the implementation of strategies; (iii) Preparing the management structure required to implement the plan with resource requirements; and (iv) Gaining the approval for the disaster waste management plan developed.

Disaster waste management could be divided into four phases as follows, as also seen in **Figure 2.7**: (i) Emergency phase addresses the most acute waste issues required to save lives, to alleviate suffering and to facilitate rescue operations. Any other considerations at this stage are secondary; (ii) Early recovery phase lays the groundwork for a disaster waste management program to be implemented during the recovery phase. It also continues to address key issues such as the location of a disposal site for the different types of waste, streamlining logistics for waste collection, transportation and reuse/recycling activities. Efforts here build on the initial emergency phase assessment but go into greater depth, with an emphasis on longer-term solutions; (iii) Recovery phase includes implementation of disaster waste management projects designed in early recovery phase, and continued monitoring and evaluation of the disaster waste situation; and (iv) Contingency planning phase is not, strictly speaking, part of emergency response. However, it does help bridge the gap between response, recovery, and longer-term development and is therefore an important investment. Contingency planning can be conducted during the recovery phase or as a preparedness measure prior to disaster.

The final objective of the disaster waste management is to remove waste (debris) in disaster affected area. Therefore debris removal operation is considered very important and urgent. The implementation of this operation faces different level of difficulties related to the authority issues, since not all debris can be managed by government authority. However only those in public areas can be relative more simply removed by the government. Cahill (2011) divided the debris removal operation into three categories relating to the property authority as follows, as seen in **Figure 2.8**: (i) Public property debris removal; is relatively simple since the debris is located on public property or on a right-of-way and does not require permission from the property owner for removal. The public property can include maintained beaches, parks, golf courses, public road, etc.; (ii) Private property debris removal; can be undertaken in certain circumstances, but significantly more documentation is involved and approval has to be given by the FEMA federal coordinating officer prior to the work done. The approval process can be very slow when an applicant is fully engaged in disaster response and other recovery work; and (iii) Private property demolition; is the most complicated debris removal category due to the volume of documentation required and the necessary involvement of many different stakeholders.

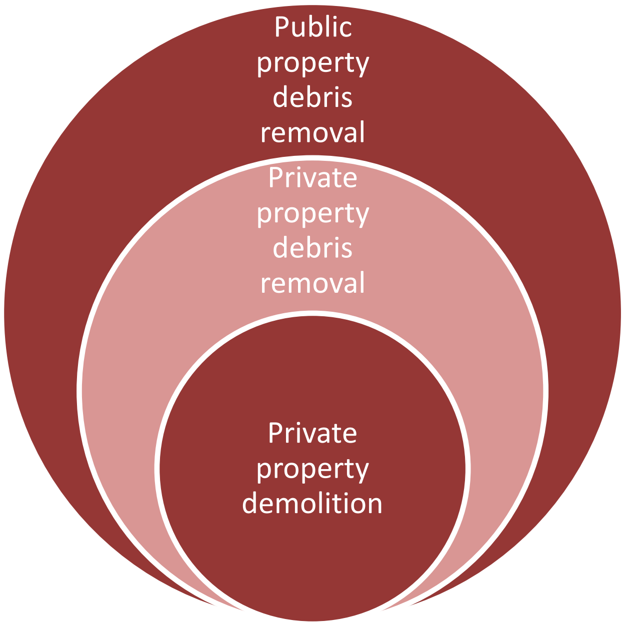


Figure 2.8 Property authority of debris removal operation

Table 2.3 The scope of research on the disaster waste management frame

<table>
<tr><td colspan="2" rowspan="2"></td><th colspan="3">PHASE</th></tr>
<tr><td>Emergency</td><td>Early recovery</td><td>Recovery</td></tr>
<tr><td rowspan="7">OPERATION</td><td rowspan="5">Public property debris removal</td><td rowspan="5">=============</td><td><s>Sorting</s></td><td rowspan="5">=============</td></tr>
<tr><td>Collection √</td></tr>
<tr><td><s>Handling</s></td></tr>
<tr><td>Transportation√</td></tr>
<tr><td><s>Treatment</s></td></tr>
<tr><td>Private property debris removal</td><td>=============</td><td>=============</td><td>=============</td></tr>
<tr><td>Private property demolition</td><td>=============</td><td>=============</td><td>=============</td></tr>
</table>

The activities of debris removal operation in disaster waste management are including the sorting, collection, handling, transportation and treatment (recovery as well as disposal) of disaster waste. The disaster debris collection operation in this research is a part of debris removal operation since as mentioned that collection and transportation to the disposal site activity are including in the debris removal operation. Therefore, from frame description of disaster waste management phases and the property authority of debris removal operation above, we narrow the scope of our research only in the early recovery phase and public property debris removal category. It is considering that the general objective research is to emphasize on the activity of debris collection and transportation that existing in the early recovery phase; and to open blockage and rebuild of road network connectivity by collecting debris in the public areas. To better understand the position of our research focus in a big frame of disaster waste management, let's see on the **Table 2.3**.

2.3.2 Lesson Learned of the Great East Japan Earthquake

The Great East Japan Earthquake in 2011 has given some lesson learned which should be considered related to the disaster waste management in general. (UNEP, 2012)

(a) Waste volume estimations

Estimating the volume of disaster debris is an important technical challenge facing any authority in the wake of a disaster. In order to scope the damage and calibrate the response, it is important that a reasonable estimate of the disaster debris is available to decision makers as quickly as possible. Debris estimates for disasters are rarely computed from ground measurements as that would be time consuming and potentially logistically challenging. Instead, estimates are generally made using satellite imagery or aerial photographs.

(b) Waste transport

It is best to keep the amount of transporting of disaster debris and number of times the debris is handled to a minimum.

(c) Land reclamation and land filling

Land reclamation and land filling are waste management options which have the potential to rapidly reduce the total volume of debris to be handled. When planned and implemented efficiently, this can be done in an environmentally acceptable and cost effective manner. Giving more flexibility to the local municipalities to use these options would potentially lower the cost and speed-up the reduction of waste volume.

(d) Handling tsunami sediments

As the seawater receded after the tsunami, it deposited a large quantity of soil on the land. Despite having many such depositions in the past which have not deterred long term land use, Japanese municipalities are scrapping the soil deposited by the tsunami without a plan for its final disposal. The decision to recover, move and dispose of the deposited soil should be based on an analysis of the physical and chemical properties of the sediments and an analysis of how the residual soil may adversely impact the future land use.

(e) Management of hazardous materials

The tsunami did not generate large quantities of hazardous materials mainly because most of the impacted areas were fishing towns or agricultural hubs. The main contributors to hazardous debris across most or all of the impacted cities were fire extinguishers, transformers and pesticides. The fear regarding radiation contamination has prevented this debris from being sent to the national hazardous waste management centers. As it would not make economic or practical sense for each municipality to establish its own hazardous waste management center, an appropriate solution would be for the impacted municipalities along the coast to collaborate and set up a single, shared Integrated Hazardous Waste Management area for the treatment and safe disposal of tsunami-related hazardous waste.

(f) Environmental monitoring

While some type of monitoring was ongoing at all locations visited by the mission team, it was not consistent. Some parameters (e.g., radiation) are monitored by the respective contractors at each site, while other parameters (e.g., asbestos) are being monitored by the government agencies off-site. It would be more appropriate to have a consistent approach to monitoring, specifying the parameters to be monitored, the protocols to be used, the frequency and external reporting requirements. More credibility and consistency could be obtained if the monitoring was undertaken by the federal government agency responsible for environmental oversight (and not the contractor or contract managing department), preferably with the support of research institutes.

(g) Support to municipalities

While the national government is underwriting the financial cost of tsunami waste treatment, the size of the debris management operation being undertaken in all of the municipalities is far beyond what is normally the task of municipal-level environment divisions. The local municipalities would benefit from a substantially increase in technical assistance, monitoring support and help with managing large-scale contracting.

(h) Local employment generation

While in-principle there is guidance to promote local employment this is not being systematically followed through. Partly due to the strict deadline given to municipalities to complete the post-disaster clean-up, there is a high degree of mechanization in the debris handling. If local employment generation is deemed a priority, there is a lot more opportunity for process optimization to maximize employment opportunities.

(i) Process optimization

The existing debris management centers could be seen as a huge industrial activity involving sequential steps with the risk that a bottleneck at one stage in the process would limit the overall progress. There is scope for reviewing the process pipeline at existing centers and any new centers, to optimize the throughput by avoiding bottlenecks in the interim steps in the process.

2.3.3 Challenges

Year by year the number of disaster events occurred in around the world significantly increased. Disaster causes a lot of loss both material and non-material, even the biggest losses caused by disasters are death and human suffering. None of area can release from disasters threats due to the nature of disasters is unpredictable time and place circumstances. What human being can do to face disasters is by anticipating and managing the risk of disasters through developing knowledge and technology, aimed to minimize losses that may occur.

Shortly after the disaster event, initial and main action which should be thought is how to save life and to ease suffering of the affected victims. As explained in the previous section, the actions to treat humankind humanely in all circumstances by saving lives and alleviating suffering while ensuring respect for the individual are well-known as humanitarian actions. Particularly, humanitarian actions can be narrow as humanitarian relief distribution operations to disaster victims in the affected area.

Humanitarian logistics is a branch of logistics which specializes in organizing the delivery and warehousing of supplies during natural disasters or complex emergencies to the affected area and people. Although they have been mostly utilized in commercial supply chain, logistics is one of the most important tools now in humanitarian relief distribution operations. Type and quantity of the resources, way of procurement and storage of the supplies, tools of tracking and means transportation to the stricken area, specialization of teams participating in the operation and plan of cooperation between these teams, are some important issues that are connected directly to the humanitarian logistics.

All natural disasters whether they involve earthquake, tsunami, flood, landslide or other natural hazards result in disaster debris. Increasingly, the management of debris generated by natural disasters is becoming a major expenditure in the immediate aftermath and longer-term recovery effort. Debris impacts the logistics of humanitarian relief and debris generated in some large-scale disasters can be equivalent in volume to years of normal solid waste production in the affected areas.

Disaster debris scattered everywhere once the disaster occurred, however based on the location where they scattered, debris can be categorized as debris which exist in public area and private area. Most of the debris scattered in public areas under the authority of the government to collect and remove them. Debris in public areas causes major problem, particularly debris that blocked the road, by interrupting or even disconnecting network connectivity. Transportation network is one of the most important issues in emergency cases such as disasters, particularly in humanitarian relief distribution operations, victim evacuation operations, as well as rebuilding the area in the recovery phase of disaster management.

As a challenge, we should agree that the debris collection operation in order to open the blockage by debris is an important operation that should be started immediately after disasters occurred. In the lesson learned of the Great East Japan Earthquake in 2001, we can find that in doing disaster debris collection and transport operation is best to keep handing to a minimum the amount of disaster debris transporting and number of times the debris. Hence, optimization in this area is important to be performed, whereby in our research is described as routing and location problem optimization. A Routing and location problem in disaster debris collection operation is an important topic related to disaster management; moreover not much research has been done in this topic. In the next section, we discuss more about some methods which are related to the methods applied in our research. To better understand about the position of our disaster debris collection operation research in the context of disaster issue; let's see on the **Figure 2.9**.

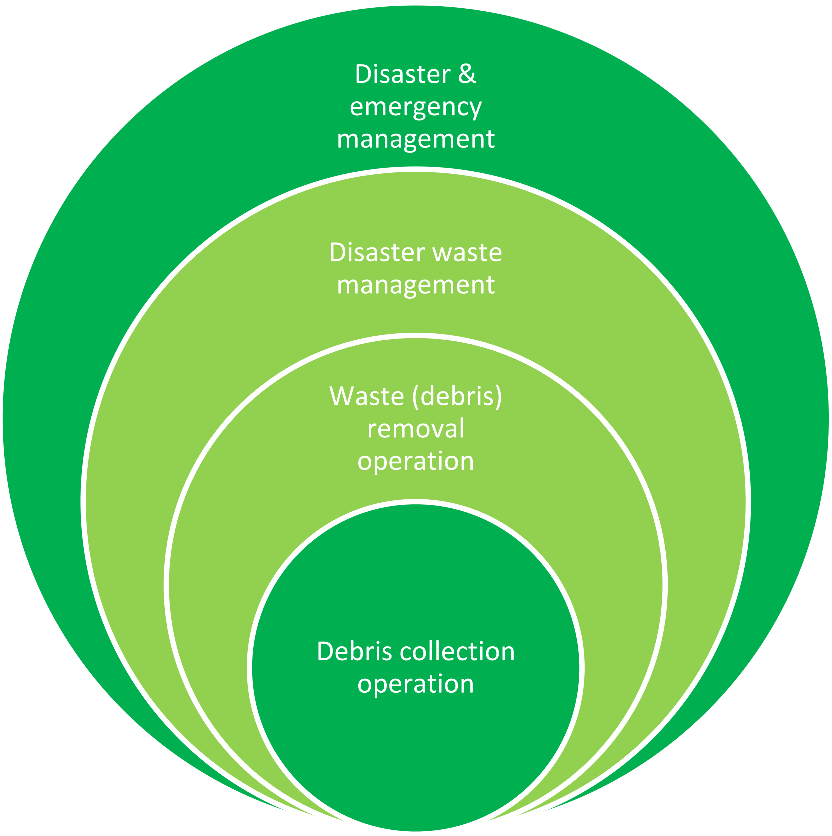


Figure 2.9 The position of our debris collection operation research

2.4 A Historical Perspective on Routing Problems

Routing is the process of selecting paths in a network along which to send network traffic. Routing is performed for many kinds of networks, including transportation networks. This section is concerned primarily with the history of route optimization, arc routing problem, capacitated arc routing problem, transformation from arc routing problem to vehicle routing problem and location-routing problem.

2.4.1 Route Optimization

Route optimization is a useful tool to optimize logistics operations due to result in outputs of the least possible number of vehicles required to serve all the demands, traveling as minimum a distance as possible and decreasing the idling time of the vehicles. The basic for route optimization is the use of models to describe the transport network that needs to be planned. When building a model, the scope of the overall network needs to be defined, ensuring that all the data is included. The model as described by Murray has a number of components such as: (i) Products. The product moves from one geographic location to another, often described as the origin and the destination. The product will be defined by its weight and its volume, which are important factors for shipping; (ii) Vehicles. A transportation network within the model can be divided into a number of sectors which is represented by a vehicle, which moves between an origin and a destination location. Each vehicle may have different attributes such as volume or weight capacity, loading times, cost per mile, and vehicle limitations, i.e., speed of the vehicle; (iii) Personnel. The personnel assigned to the model have characteristics that are governed by the type of work they perform.

2.4.2 Arc Routing Problem

Arc routing problem consist of determining a least cost traversal of some arcs or edges of a graph, subject to side constraints. Such problems are encountered in a variety of practical situations such as road or street maintenance, garbage collection, mail delivery, school bus routing, meter reading, etc. Billions of dollars each year were spent on arc routing operations, mainly by public administrations, and there exists a sizeable potential for savings. In recent years, new advances in optimization techniques and in computer technology have contributed to the dissemination and adoption of sophisticated arc routing software. Nowadays, commercial packages make heavy use of rich data bases, geographical information systems, and interactive graphic interfaces. It is not exaggerated to affirm that there now exist a thriving arc routing industry, mostly sustained by consultancy firms. (Dror, 2000)

Many surveys can be found explaining many arc routing problem variants, however the three main variants are Chinese Postman Problem (CPP) in which it is required to traverse all arcs of a graph; Rural Postman Problem (RPP) in which only a subset of arcs must be traversed; and the Capacitated Arc Routing Problem (CARP) which is a capacity constrained version of the two earlier variants with multiple real life applications, as reviewed in detail in Cordeau and Laporte (2002); Dror (2000); Eislet et al. (1995); Assad and Golden (1995). Since CARP is an underlying of the problem exists in our research, we narrow search limited only in this variant.

2.4.3 Capacitated Arc Routing Problem

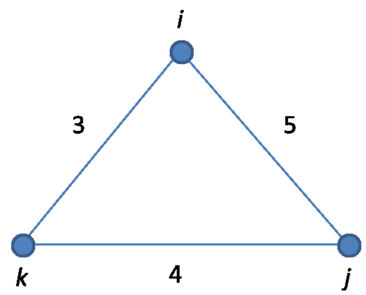
In the CARP, a non-negative quantity q_{ij} is associated with each arc or edge (i, j). A fleet of m vehicles, each having a capacity Q, must traverse all arcs or edges of the graphs and collect (or deliver) the associated quantities, without ever exceeding Q. As in the standard Vehicle Routing Problem (VRP), the number of vehicles may be given a priori or can be a decision variable. The CARP was introduced by Golden and Wong (1981), but a variant in which all $q_{ij}$are strictly positive was investigated earlier by Christofides (1973). In other words, the CARP studied by Golden and Wong (1981) and the majority of subsequent researchers can be viewed as a capacity constrained RPP with m vehicles, whereas the problem defined by Christofides (1973) is a capacity constrained CPP with m vehicles.

Many variations of the classical CARP can be considered. Each of the variations considered reflects situations occurring in real life applications, such as: (i) CARP defined on directed or mixed graphs; (ii) CARP with alternative objective functions including Min-Max k-CPP, which is a CARP like problem with several vehicles but excluding capacity constraints; (iii) CARP with including time window constraints; (iv) CARP with multiple depots and with mobile depots, respectively; (v) A version of CARP, where not all vehicles are able to service all edge; (vi) The periodic CARP is considered; (vii) A stochastic version of the CARP. The detail of each CARP variant can be reviewed in Wøhlk (2008).

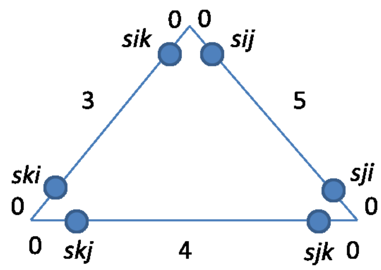
2.4.4 Transformation of ARP to VRP

The theory of complexity of combinatorial problems such as CARP classifies problems as “hard” for not known to be solvable in polynomial time complexity; or “easy” for which known polynomial time procedures exist with guarantee of reaching an optimal solution. Thus in principle, one can transform in polynomial time any arc routing problem to a Traveling Salesman Problem (TSP) version (instance). However, for arc routing problems which are NP-hard, it might be of computational interest to examine solution schemes in their transformed node routing image. For the arc routing problems with time windows, this is absolutely essential. Moreover, for some arc routing problems, like Mixed RPP and the Stacker Crane Problem, the only known exact method, uses a transformation into node routing problems. (Dror, 2000)

Solving CARP in our research begins with transforming the CARP graph into an equivalent Capacitated Vehicle Routing Problem (CVRP) graph. The transformation is performed to formulate the problem more easily in terms of mathematical algorithm since a vast literature exists for the CVRP topic as compared to the CARP. In a well-known transformation by Pearn et al. (1987) an arc in CARP was represented by three nodes in the equivalent CVRP. Meanwhile, Baldacci and Maniezzo (2006); and Longo et al. (2006) used the type of CARP transformation into CVRP with making two nodes for each required arc, whereby the illustrations can be seen in **Figure 2.10**.



Original CARP graph



Transformed CVRP graph

Figure 2.10 CARP transformation into CVRP

2.4.5 Location-Routing Problem

Location factor particularly the location of depot facility is also become determinants in optimization in routing problem. Location-Routing Problem (LRP) is a relatively new branch of location analysis that takes into account vehicle routing aspects. It is not a single well defined problem like the TSP, however it can be thought of as a set of problems within location theory. The LRP is preferred to think as an approach to modeling and solving location problem.

Nagy and Salhi (2007) defined location-routing, following Bruns (1998), as location planning with tour planning aspects taken into account. The definition stems from a hierarchical viewpoint, whereby the aim was to solve a facility location problem (the master problem), but in order to achieve this, a vehicle routing problem (the sub problem) simultaneously need to be solved. This also implied an integrated solution approach, i.e., an approach that did not only deal with both location and routing aspects of a problem but also addressed their inter-relation. Another important characteristic of the definition was the requirement for the existence of tour planning, i.e., the existence of multiple stops on routes. This occurs if customer demands are less than a full truckload.

Nagy and Salhi's (2007) also stated that LRP was clearly related to both the classical location problem and vehicle routing problem. In fact, both of the latter problems could be viewed as special cases of the LRP. If all customers were required to be directly linked to a depot, the LRP became a standard location problem. If, on the other hand, the depot locations were fixed, the LRP reduces to a VRP. From a practical viewpoint, location-routing forms part of collection or distribution management, while from a mathematical point of view, it can usually be modeled as a combinatorial optimization problem. Locations, if associated with our research, are the location of disposal sites which is as vehicle's destination point to dump the debris.

2.5 Methodology

We research a variant of the undirected Capacitated Arc Routing Problem (CARP). The problem in this research is motivated from disaster debris collection operation; for that a modification in classical CARP is required. In this new CARP variant, roads are treated as a set of arcs. A set of required arcs consists of arcs that are covered by debris, thus they have demands to service. The objective function of the CARP is to service all required arcs in the graph at least cost with feasible vehicle routes. The modification of the classical CARP results in a disaster debris collection operation model which has objective to minimize the operational cost through optimization of vehicle routing and disposal site location.

Objectives of the research are: (i) to enhance and to enrich the topic of research in humanitarian logistics more on the topic of disaster debris removal (collection) operation; (ii) to modify classical CARP into disaster debris collection operation problem by adding new constraint i.e., access possibility constraint (which is classified into the family of dynamic constraint); (iii) to apply the resulting model formulation for solving artificial small problem instances using tabu search meta-heuristics; and (iv) to apply the resulting model formulation for solving a realistic case study, in order to evaluate the compatibility of the model with the real case problems. The structure of literature review of methodology can be seen in **Figure 2.11**.

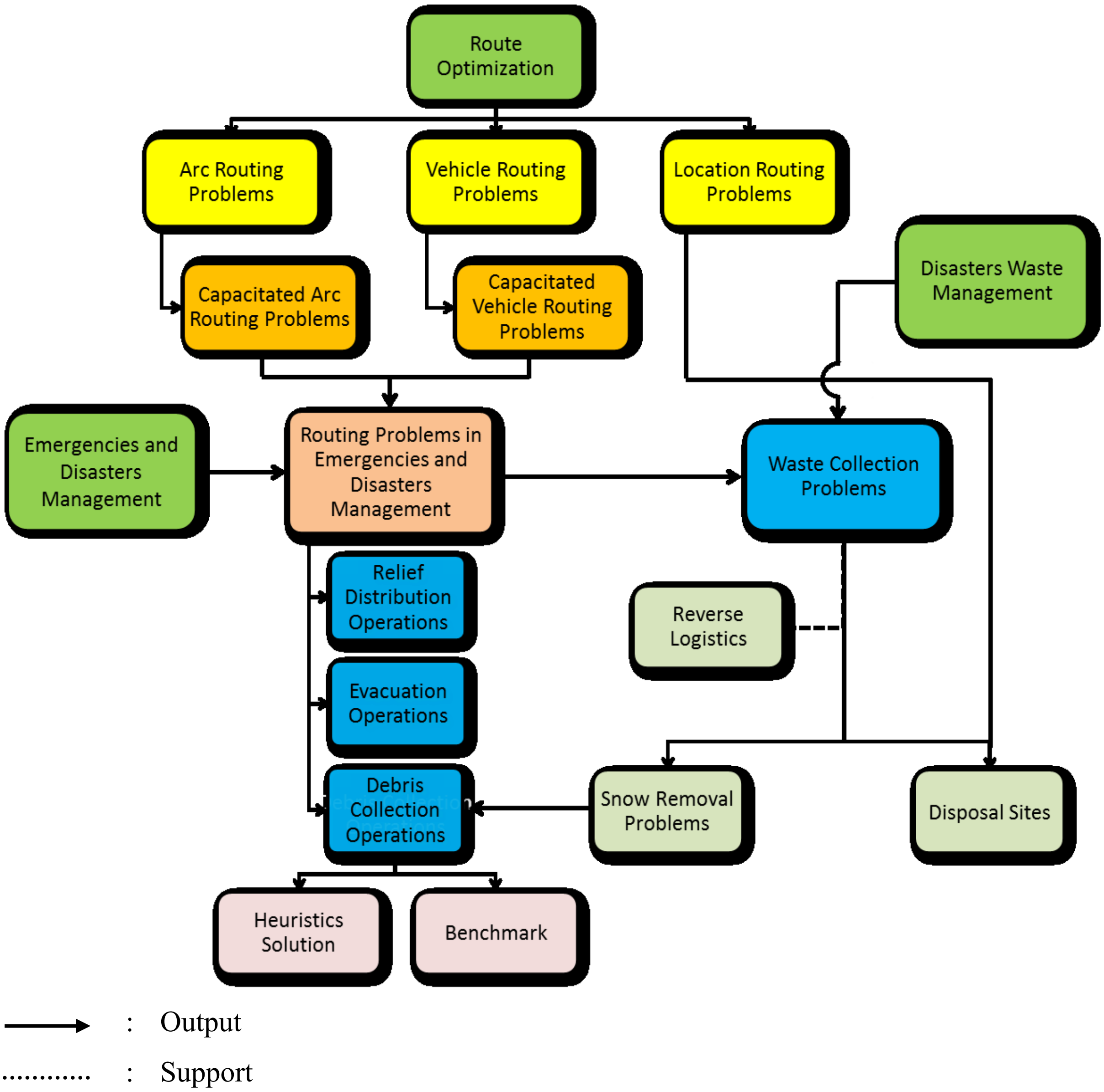


Figure 2.11 Methodology

The scheme shows that route optimization can be categorized into three groups i.e., arc routing problem, vehicle routing problem and location routing problem. One of the well-known variants of the arc and vehicle routing problem is the problem with capacity constraint called as CARP and CVRP. Both are in fact closely related, the main difference being that in the CARP customers are set of arcs while in the CVRP customers are set of nodes. In association with the routing problem in disaster and emergency and management issues, a vast literature exists for relief distribution and evacuation operation. However, disaster debris collection operation literature has not much been research so far. Actually, the debris collection operation is a part of waste collection problem, which is a family of reverse logistics. We focus reviewing on the topic of waste collection problem which have close connection to our disaster debris collection operation research i.e., snow removal problem due to their similarity; and disposal sites problem as an important issue in location routing problem. The problem is solved by using tabu search meta-heuristics method. Therefore to assess the accuracy of the algorithm more conclusively, we compared the result with some benchmark.

2.5.1 Routing Problem in Disaster and Emergency Management

In association with the routing problem in disaster and emergency management issues, a vast literature exists for relief distribution and evacuation operation. However, debris collection operation literature has not much been research so far. Actually there is a strong connection among such operations performed in the context of humanitarian. Particularly for the debris collection operation would support and speed up the other operations due to rebuild better road connectivity. Some following literature discuss about routing problem in humanitarian, particularly related to relief distribution and evacuation operation.

(a) Relief Distribution Operation

Some literature reviewed about routing problem in relief distribution operation as follows. Wohlgemuth et al. (2012) considered the application of a routing and scheduling problem for forwarding agencies handling less-than-truckload freight in disasters. The approach evaluated the benefits of dynamic optimization anticipating varying travel times (i.e., the availability of connections in this case) as well as unknown orders (i.e., the integration of demand regions on short notice) in the specific environment of emergencies. The objective was to avoid delays and increase equipment utilization. They modeled a multi-stage mixed integer problem which was able to operate under variable demand and transport conditions.

Sheu (2007) presented a hybrid fuzzy clustering-optimization approach to the operation of emergency logistics co-distribution responding to the urgent relief demands in the crucial rescue period. Based on a proposed three-layer emergency logistics co-distribution conceptual framework, the proposed methodology involved two recursive mechanisms: (i) disaster-affected area grouping, and (ii) relief co-distribution. Numerical studies with a real large-scale earthquake disaster occurring in Taiwan were conducted, and the corresponding results indicate the applicability of the proposed method and its potential advantages.

Yi and Kumar (2007) presented a meta-heuristic of ant colony optimization for solving the logistics problem arising in disaster relief activities. The logistics planning involved dispatching commodities to distribution centers in the affected areas and evacuating the wounded people to medical centers. The proposed method decomposed the original emergency logistics problem into two phases of decision making, i.e., the vehicle route construction, and the multi-commodity dispatch. The sub-problems were solved in an iterative manner. The first phase built stochastic vehicle paths under the guidance of pheromone trails while a network flow based solver was developed in the second phase for the assignment between different types of vehicle flows and commodities. The performance of the algorithm was tested on a number of randomly generated networks and the results indicated that this algorithm performed well in terms of solution quality and run time.

(b) Evacuation Operation

Some literature reviewed about routing problem in evacuation operation as follows. Yi and Odamar (2007) described an integrated location-distribution model for coordinating logistics support and evacuation operations in disaster response activities. Logistics planning in emergencies involved dispatching commodities (e.g., medical materials and personnel, specialized rescue equipment and rescue teams, food, etc.) to distribution centers in affected areas and evacuation and transfer of wounded people to emergency units. During the initial response time it was also necessary to set up temporary emergency centers and shelters in affected areas to speed up medical care for less heavily wounded survivors. In risk mitigation studies for natural disasters, possible sites where these units could be situated are specified according to risk based urban structural analysis. Logistics coordination in disasters involved the selection of sites that result in maximum coverage of medical need in affected areas.

Another important issue that arises in such emergencies was that medical personnel who were on duty in nearby hospitals have to be re-shuffled to serve both temporary and permanent emergency units. Thus, an optimal medical personnel allocation must be determined among these units.

2.5.2 Waste Collection Operation Routing Problem

Waste collection operation is underlying of our disaster debris collection operation due to their similarity, but in different situation and condition. Waste collection operation itself is part of reverse logistics considering the nature, which does not deliver goods to the customers but more on collecting from, to the designated points, termed as disposal sites. The required locations in waste collection operation can be either at nodes as pick-up points, or along arcs. Particularly for the second case, we discuss it from the literature review of snow removal operation in the next section. The snow removal operation is considered quite similar to the waste collection operation due to customers are along the arcs.

(a) Reverse Logistics

Reverse logistics was defined by Rogers and Tibben-Lembke (2001) as the process of planning, implementing and controlling the efficient and cost effective flow of raw materials, in-process inventory, finished goods, and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal. More precisely, reverse logistics was the process of moving goods from their typical final destination for the purpose of capturing value, or proper disposal.

Reverse logistics is primarily used as a tool for management in an appropriate manner all kinds of waste. In the context of logistics, the disaster debris collection operation is a family of reverse logistics, which stands for all operations related to the reuse of products and materials. However, there are some fundamental different between reverse logistics in commercial waste management and in disaster area. Balcik and Beamon (2008) distinguished the humanitarian logistics and commercial logistics in some aspects as follows: (i) Unpredictable demand in terms of timing, geographic location, type of commodity, quantity of commodity; (ii) Short lead time and suddenness of demand for large amounts of a wide variety of products and services; (iii) High humanitarian stakes regarding timelines in the face of a sophisticated global media and the high anticipatory attention of the donors; (iv)

Lack of initial resources in terms of supply, human resource, technology, capacity and funding.

Most of the authors in some literature propose a reverse logistics system with four main steps i.e., gate keeping (entry), collection, sorting, and disposal. Since our research is more focused on the routing and location problem of disposal sites, thus only collection and disposal topic in reverse logistics would be reviewed. Debris as result of the disaster in our research could also be considered as municipal solid waste. Moreover, developing a reverse logistics solid waste management model to manage the interactions among transport planning, and inventory features and production planning in the entire system under uncertainties would be highly preferred. A relevant literature about reverse logistics model for municipal solid waste management systems was well reviewed by Zhang (2010).

(b) Disposal Site

A disposal site in this research is termed as an intermediate depot, which is distinguished from depot when viewed from the purposes. The problem in our research is a modification of classical CARP, therein vehicles with varying capacity, move out from depot, service some of the required arcs and return to depot at the end of their tour. Each vehicle is not allowed to take load exceeding its capacity, to continue its tour it must unload at a designated point first, which could be an intermediate depot.

The idea of the intermediate depot came from Crevier et al. (2005), where the interest arose from a real-life grocery distribution problem in the Montreal area. Several similar applications were encountered in the context where the route of a vehicle could be composed of multiple stops at intermediate depots in order for the vehicle to be replenished. When trucks and trailers were used, the replenishment could be done by a switch of trailers.

Angelelli and Speranza (2002) presented an application of a similar problem in the context of waste collection. The study was an extension of the Periodic Vehicle Routing Problem (PVRP) where the vehicles could renew their capacity at some intermediate facilities. The vehicles returned to the depot only when the work shifts were over. When the capacity limit was reached the vehicles renew their capacity by unloading the waste at one of the treatment plants or the intermediate depots.

(c) Snow Removal Operation

Areas with severe winters face each year the difficult task of clearing snow and ice from their streets. Problems arising in winter road maintenance are complex, costly, and site-specific because of the variations of climatic conditions, demographics, economics, and technology. According to Perrier et al. (2006), the importance of winter road maintenance is due to the magnitude of the expenditures associated to these operations, and to the indirect costs resulting from the loss of productivity and decreased mobility. There exists a relatively limited scientific literature on the practical aspects of snow removal operation. Here we concentrate on the most important publications of the past ten years.

Golbaharan (2001) has studied a multi-depot snow removal routing problem with time windows. This problem consists of designing a set of least cost routes for homogeneous snow plows, while covering every required road segment exactly once within its associated time window. Every snow plow starts its route at a depot and returns to the same depot. The performance of the proposed solution procedure was evaluated on real-life data. Similar problems have also been studied by Sochor and Yu (2004); and Razmara (2004). Perrier et al. (2006) have proposed a formulation and two solution approaches based on mathematical optimization techniques for the routing of snow plowing vehicles in urban areas. Fu et al. (2009) have developed a real-time optimization model to evaluate alternative resources allocation plans for winter road maintenance operations. The paper by Dali (2009) proposes a sequential constructive heuristic for the design of snow plow routes in a multi-depot network. The minimization of the total deadhead distance is carried out under some side constraints such as service continuity, both-sides service, vehicle capacity, and maximal time for service completion. Finally, Jang et al. (2010) have proposed a formulation and a heuristic for a combined depot location, sector design, spreading and plowing route design, fleet configuration and vehicle scheduling problem. Their heuristic integrates depot and sector selection, initial route construction, route improvement, fleet configuration, and scheduling. It iteratively solves these problems until no better solution can be found.

2.5.3 Disaster Debris Collection Operation Routing Problem

As discussed in the previous section, the problem on snow removal operation is similar to the problem in our research. For that, we adopted some part of model formulation from study by Tagmouti et al. (2007) and modify it according to the need in solving the problem of disaster debris collection operation. To show the novelty of disaster debris collection operation in this research, let us compare it with the snow removal operation problem in Tagmouti et al. (2007), which is similar with our problem. The fundamental difference between disaster debris collection operation and snow removal operation is described as follows. In snow removal operation, the timing of the intervention is of prime importance. That is, if the intervention is too early or too late, the cost in material and time sharply increases. On the other hand, in disaster debris collection operation, because some accesses are blocked by the debris, sequence in visiting and servicing arcs at the previous road network structure affect aggregate accessibility at the next one. Clearly mentioned that blocked access by the debris is the uniqueness of the problem exists in our research. Another study which has similar problem related to the blocked access has done by Ergun et al. (2009), about management of debris collection and disposal operations.

Back to the concept of general debris removal operations, such operations occur in three phases as follows, as also seen in **Figure 2.12**: (i) Debris clearance refer to operations performed during or right after a hazardous event with the goal of clearing the debris from major arteries to give access to critical facilities and to aid in emergency relief operations; (ii) Debris collection refer to transportation of the debris from the disaster area to collection sites. This phase must be done in a timely fashion as long-term standing debris can cause serious risks to the affected area, including threat of disease or chemicals spilling into the environment; (iii) Debris disposal refer to transportation of the debris to the final disposal sites and the choice of the disposal method (e.g., landfill, reduce, recycle or reuse) for a given debris type at a given location.

The scope of our research is in debris clearance and collection phase only, while disposal phase is detained due to does not include in the logistics and transportation issues. Actually, in the early phase just after the disasters occurred, some roads must be cleared but merely for emergency purposes, such as evacuation and relief distribution. Such debris removal operation will move debris on the road to roadsides. However, the debris removal operation in this study is a comprehensive operation in order to reopen the road and rebuild road connectivity as an operation in disaster management in early recovery phase.

In the debris clearance phase, Ergun et al. (2009) defined road network condition, clearance capacity per period, debris amounts, relief supply or demand locations and quantities as inputs. The objective was minimizing penalty due to unsatisfied demand, with complete debris information that all debris amounts assumed to be known; and incomplete debris information that reachable arcs has known debris amounts, beliefs about unreachable

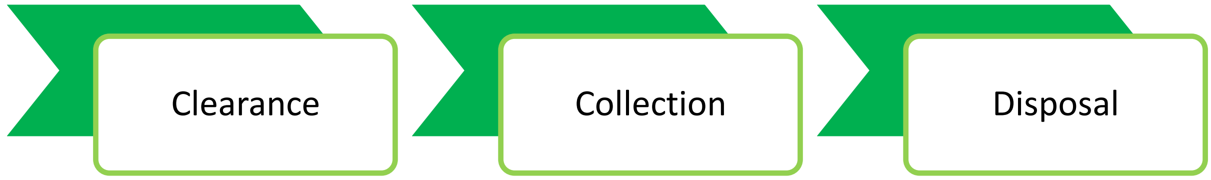


Figure 2.12 Debris operations phases

arcs, updated as clearance proceeds. The information would be regionally updated as arcs in the same region became reachable. Finally, a set of roads to be cleared and clearance sequence were obtained as output in this phase.

Meanwhile in the debris collection phase, Ergun et al. (2009) defined debris amounts, facility locations and capacities, contractor data as inputs. The objective was minimizing cost and completion time. Finally, the output as fair and continuous assignment of the roads to collection teams and expected collection time was solved by Mixed Integer Programming (MIP) based sequential heuristics.

2.5.4 Heuristics Solution Approach of Route Optimization

(a) History of Heuristics

Heuristics, i.e., approximate solution techniques, have been used since the beginnings of operations research to tackle difficult combinatorial problems. With the development of complexity theory in the early 70's, it became clear that, since most of these problems were indeed NP-hard, there was little hope of ever finding efficient exact solution procedures for them. This realization emphasized the role of heuristics for solving the combinatorial problems that were encountered in real-life applications and that needed to be tackled, whether or not they were NP-hard. While many different approaches were proposed and experimented with, the most popular one was based on local search improvement techniques. Local search can be roughly summarized as an iterative search procedure that, starting from an initial feasible solution, progressively improves it by applying a series of local modifications (or moves). At each iteration, the search moves to an improving feasible solution that differs only slightly from the current one (in fact, the difference between the previous and the new solutions amounts to one of the local modifications mentioned above). The search terminates when it encounters a local optimum with respect to the transformations that it considers, an important limitation of the method: unless one is extremely lucky, this local optimum is often a fairly mediocre solution. In local search, the quality of the solution obtained and computing times are usually highly dependent upon the “richness” of the set of transformations (moves) considered at each iteration of the heuristic.

(b) Tabu Search Meta-heuristics

Building upon some of his previous work, Glover (1986) proposed a new approach, which he called tabu search, to allow local search methods to overcome local optimum. (In fact, many elements of this first tabu search proposal, and some elements of later tabu search elaborations, were introduced in Glover (1977), including short term memory to prevent the reversal of recent moves, and longer term frequency memory to reinforce attractive components.) The basic principle of tabu search is to pursue local search whenever it encounters a local optimum by allowing non-improving moves; cycling back to previously visited solutions is prevented by the use of memories, called tabu lists that record the recent history of the search, a key idea that can be linked to artificial intelligence concepts. It is interesting to note that, the same year, Hansen proposed a similar approach, which he named steepest ascent or mildest descent. It is also important to remark that Glover did not see tabu search as a proper heuristic, but rather as a meta-heuristic, i.e., a general strategy for guiding and controlling “inner” heuristics specifically tailored to the problems at hand.

(c) Solomon’s Benchmark Instances

To measure the quality of solution resulted from the calculation using heuristics method, one needs to compare it with some benchmark. A well-known benchmark instances for VRP were developed by Solomon (1987). The instances are sets of problems with data such as geographical, the number of customers serviced by a vehicle, percent of time-constrained customers, and tightness and positioning of the time windows. These instances are the most widely used test instances in VRP with time windows-related research to test the worst-case behavior of various algorithms. Divided into two series (series1 and series2), the problems are classified as Random or R-type (R1 and R2), Clustered or C-type (C1 and C2) and mixed random or clustered or RC-type (RC1 and RC2). As also reviewed in Qureshi (2008), the R-type (R1 and R2) problems have randomly generated locations of the customers (**Figure 2.13**), C-type (C1 and C2) have cluster groups of customers (**Figure. 2.14**) whereas RC (RC1 and RC2) have a mix of clustered as well as randomly located customers as shown in **Figure 2.15**, depot is represent by circular vertex.

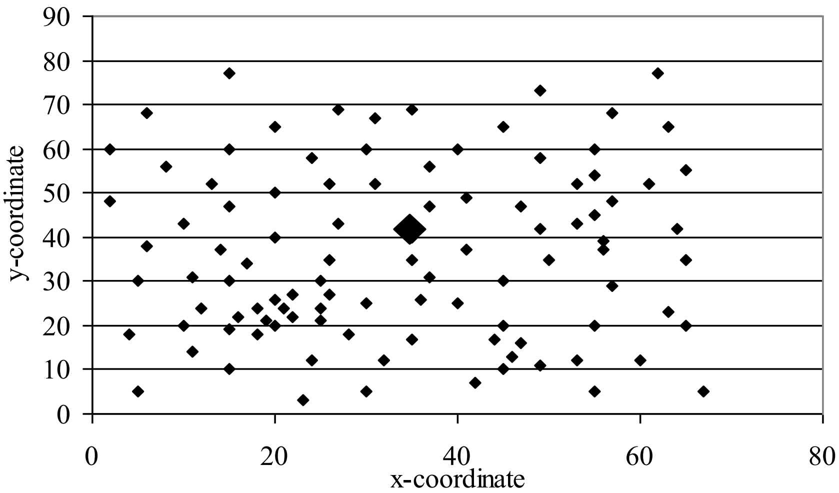


Figure 2.13 Customers' location in R-type Solomon's benchmark instance

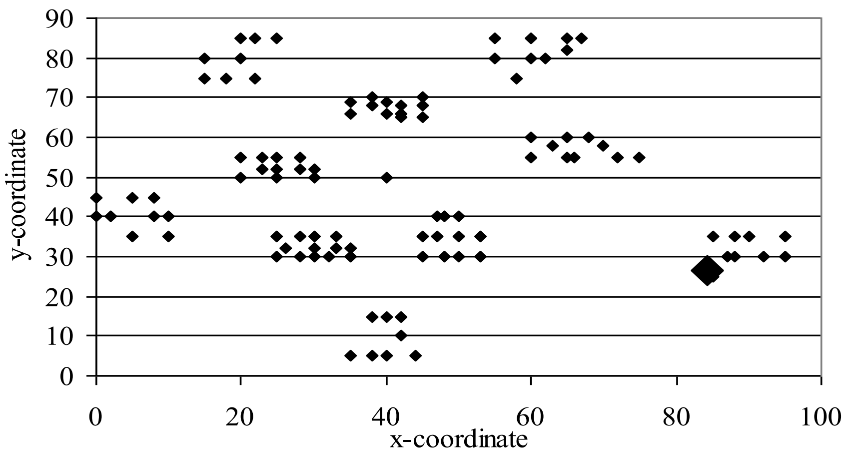


Figure 2.14 Customers' location in C-type Solomon's benchmark instance

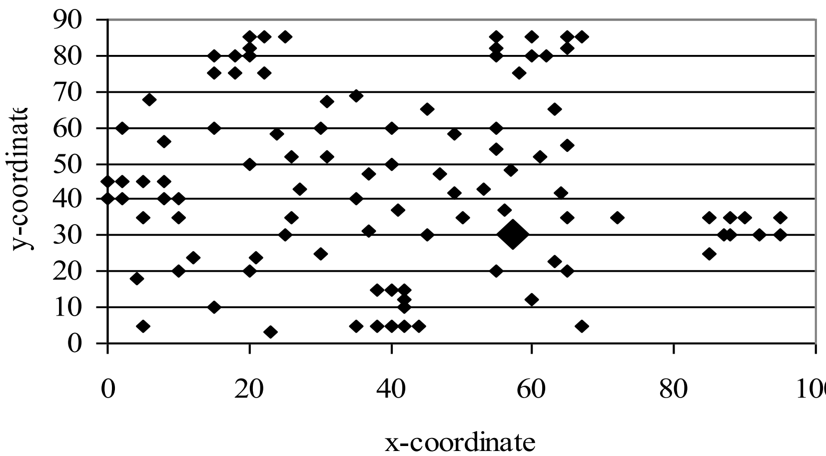


Figure 2.15 Customers' location in RC-type Solomon's benchmark instance

In total there are 56 bench mark instances; R-type has 12 instances in series 1 (marked as R101, R102 and so on) and 11 instances in series 2, C-type has 9 instances in series 1 (marked as C101, C102 and so on) and 8 instances in series 2, and RC-type has 8 instances in each series (marked as R101, R102 and so on). All instances of a same type i.e., R-type, C-type or RC-type, have same locations (as shown in **Figures 2.13** to **2.15**) in each series, whereas it differs from the other problems in same type by the percentage of customers (25, 50, 75 and 100%) with binding time windows. Finally the series 1 corresponds to short scheduling horizon with a vehicle capacity of 200 and the series 2 is made to represent long scheduling horizons with larger time windows as compared to series 1 and setting vehicle capacity as 1000. Each instance consists of 100 customers, whereas, smaller instances are formulated by considering first 25 (e.g., R101-25) or 50 customers (e.g., C101-50) from each instances.

2.6 Summary

There is no area that is immune from disaster, though vulnerability to disaster varies. As an representation case, Asia is the world's most disaster-prone region, and Asia's poor, lacking in resources and more vulnerable and exposed to the elements, have borne the brunt of the region's cataclysms. Natural disasters can strike anywhere, however Asia's poor and those living in poor countries with weak governance and economies get hit the most. ADB (2011) reported more than 2,200 natural disasters struck Asia in the past 20 years, claiming close to one million lives.

FEMA (2007) reported that the concerning and legislation of disaster and emergency management was starting from the Congressional Act of 1803. In March 2003, FEMA along with twenty two other agencies, programs and office became the Department of Homeland Security. This new department, headed by Secretary Tom Ridge, brought a coordinated approach to national security from emergencies and disaster both natural and man-made. Disaster and emergency management refers to the policies, programs, administrative actions and operations undertaken to address a natural or man-made disaster through preparedness, mitigation, response and recovery.

The basic task of a logistics system is to deliver the appropriate supplies, in good condition, in the quantities required, and at the places and time they are needed, therefore logistics plays a critical role in disaster and emergency management. A branch of logistics which specializes in organizing the delivery and warehousing of supplies during natural disasters or complex emergencies to the affected area and people is recognized as humanitarian logistics. Humanitarian logistics was defined by Thomas and Mizushima (2005) as the process of planning, implementing and controlling the efficient, cost-effective flow and storage of goods and materials as well as related information, from the point of origin to the point of consumption for the purpose of meeting the end beneficiary's requirements.

One of the important roles of logistics during the disaster response phase is on the humanitarian relief operation. Another important role of logistics is on the debris removal (collection) operation which can be considered as an operation to remove the debris which blocks road in order to rebuild access connectivity. The access connectivity is highly impacts on humanitarian relief distribution process. In case of debris blocked road and disrupt the access connectivity, the humanitarian relief distribution would experience deceleration.

Disaster-generated waste was defined in FEMA (2007) as any material, including trees, branches, personal property and building material on public or private property that was directly deposited by the disaster. Disaster-generated waste could also be termed as debris. Depending on the context, however in this research, debris can refer to a number of different things as result of disaster.

Disaster waste management is the process which consists of: (i) Determining the appropriate response and recovery strategies to be implemented after a disaster (based on assessments of vulnerability); (ii) Identifying and agreeing responsibility for the implementation of strategies; (iii) Preparing the management structure required to implement the plan with resource requirements; and (iv) Gaining the approval for the disaster waste management plan developed.

The activities of debris removal operation in disaster waste management are including the sorting, collection, handling, transportation and treatment (recovery as well as disposal) of disaster waste. The debris collection operation in this research is a part of debris removal operation since as mentioned that collection and transportation to the disposal site activity are including in the debris removal operation. Therefore, from frame description of disaster waste management phases and the property authority of debris removal operation above, we narrow the scope of our research only in the early recovery phase and public property debris removal category. It is considering that the objective research is to emphasize on the activity of debris collection that existing in the early recovery phase; and to open blockage and rebuild of road network connectivity by collecting debris in the public areas.

As a challenge, we should agree that the debris collection operation in order to open the blockage by debris is an important operation that should be started immediately after disasters occurred. In the lesson learned of the Great East Japan Earthquake in 2011, we can find that in doing disaster debris collection and transport operation is best to keep handing to a minimum the amount of disaster debris transporting and number of times the debris. Hence, optimization in this area is important to be performed, whereby in our research is described as routing and location problem optimization. A Routing and location problem in disaster debris collection operation is an important topic related to disaster management; moreover not much research has been done in this topic. In the next section, we discuss more about some methods which are related to the methods applied in our research.

Route optimization is a useful tool to optimize logistics operations due to result in outputs of the least possible number of vehicles required to serve all the demands, traveling as minimum a distance as possible and decreasing the idling time of the vehicles.

Arc routing problem consist of determining a least cost traversal of some arcs or edges of a graph, subject to side constraints. Such problems are encountered in a variety of practical situations such as road or street maintenance, garbage collection, mail delivery, school bus routing, meter reading, etc.

Many surveys can be found explaining many arc routing problem variants, however the three main variants are Chinese Postman Problem (CPP) in which it is required to traverse all arcs of a graph; Rural Postman Problem (RPP) in which only a subset of arcs must be traversed; and the Capacitated Arc Routing Problem (CARP) which is a capacity constrained version of the two earlier variants with multiple real life applications, as reviewed in detail in Cordeau and Laporte (2002); Dror (2000); Eislet et al. (1995); Assad and Golden (1995). Since CARP is an underlying of the problem exists in our research, we narrow search limited only in this variant.

Location factor, particularly the location of depot facility, is also become determinants in optimization in routing problem. Location-Routing Problem (LRP) is a relatively new branch of location analysis that takes into account vehicle routing aspects. It is not a single well defined problem like the TSP, however it can be thought of as a set of problems within location theory. The LRP is preferred to think as an approach to modeling and solving location problem.

We research a variant of the undirected Capacitated Arc Routing Problem (CARP). The problem in this research is motivated from disaster debris collection operation; for that a modification in classical CARP is required. In this new CARP variant, roads are treated as a set of arcs. A set of required arcs consists of arcs that are covered by debris, thus they have demands to service. The objective function of the CARP is to service all required arcs in the graph at least cost with feasible vehicle routes. The modification of the classical CARP results in a disaster debris collection operation model which has objective to minimize the operational cost through optimization of vehicle routing and disposal site location.

The problem on snow removal operation is similar to the problem in our research. For that, we adopted some part of model formulation from study by Tagmouti et al. (2007) and modify it according to the need in solving the problem of disaster debris collection operation. To show the novelty of disaster debris collection operation in this research, let us compare it with the snow removal operation problem in Tagmouti et al. (2007), which is similar with our problem. The fundamental difference between disaster debris collection operation and snow removal operation is described as follows. In snow removal operation, the timing of the intervention is of prime importance. That is, if the intervention is too early or too late, the cost in material and time sharply increases. On the other hand, in disaster debris collection operation, because some accesses are blocked by the debris, sequence in visiting and servicing arcs at the previous road network structure affect aggregate accessibility at the next one.

Tabu search meta-heuristics is a chosen approach to solve the disaster debris collection operation problem. To measure the quality of solution resulted from the calculation using heuristics method, one needs to compare it with some benchmark. A well-known benchmark instances for vehicle routing problem were developed by Solomon (1987).

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Chapter 3

The Mathematical Model of Disaster Debris Collection Operation

3.1 Introduction

A mathematical model is a description of a system using mathematical concepts and languages. The process of developing a mathematical model is termed mathematical modeling. A model may help to explain a system and to study the effects of different components, and to make predictions about behavior. Mathematical models can take many forms, including but not limited to dynamical systems, statistical models, differential equations, game theoretic models, routing problems and so on. These and other types of models can overlap, with a given model involving a variety of abstract structures. In general, mathematical models may include logical models, as far as logic is taken as a part of mathematics. In many cases, the quality of a scientific field depends on how well the mathematical models developed on the theoretical side agree with results of repeatable experiments. Lack of agreement between theoretical mathematical models and experimental measurements often leads to important advances as better theories are developed.

3.2 Basic Ideas

As a basic idea in the mathematical model of disaster debris collection operation is that the new model proposed in this research is a modification of the classical model of Capacitated Arc Routing Problem (CARP).

3.2.1 Classical Model of Capacitated Arc Routing Problem

Arc routing problem consists of determining a least cost traversal of some specified arcs of a graph, subject to side constraints. Such problems are encountered in variety of practical situation such as road or street maintenance, winter gritting operation, waste collection, mail delivery, school bus routing, utility meter reading, etc. Many surveys can be found explaining many arc routing problem variants, however the three main variants are Chinese Postman Problem (CPP) in which it is required to traverse all arcs of a graph; Rural Postman Problem (RPP) in which only a subset of arcs must be traversed; and the CARP which is a capacity constrained version of the two earlier variants with multiple real life applications, as reviewed in detail in Cordeau and Laporte (2002); Dror (2000); Eislet et al. (1995); Assad and Golden (1995).

The CARP is the problem of servicing a set of arcs in a network using a fleet of capacity constrained vehicles initially located at a central depot. The objective of the problem is to minimize the total routing cost. Theoretically, the CARP is an arc routing counterpart to the Capacitated Vehicle Routing Problem (CVRP) and has been proved to be NP-hard (non-deterministic polynomial-time hard). In CARP, vehicles with varying capacity, move out from depot, service some of the required arcs and return to depot at the end of their tour. Each vehicle is not allowed to take load exceeding its capacity, to continue its tour it must unload at a designated point first, which could be an intermediate depot.

3.2.2 Modification Part

The disaster debris collection operation is a new in this area and not much research has been done in this topic. The debris collection operation actually is a family of reverse logistics as reviewed in Cardoso et al. (2012); and Hu et al. (2002), considering that the process is moving goods from their typical final destination for the purpose of capturing value, or proper disposal.

To show the novelty of disaster debris collection operation in this research, let us compare it with the snow removal operation problem in Tagmouti et al. (2007), which is similar with our problem. The fundamental difference between disaster debris collection operation and snow removal operation is described as follows. In snow removal operation, the timing of the intervention is of prime importance. That is, if the intervention is too early or too late, the cost in material and time sharply increases. On the other hand, in disaster debris collection operation, because some accesses are blocked by the debris, sequence in visiting and servicing arcs at the previous road network structure affect aggregate accessibility at the next one. Besides studied by Tagmouti et al. (2007), many important publications of the past ten years related to the snow removal operation problem have been well reviewed by Aguilar et al. (2012).

Therefore, the uniqueness of this kind of CARP problem is due to the limited access from one section to the others, as a result of the blocked access by debris. A modification in classical CARP is therefore, required to solve this kind of problem i.e., by adding a new constraint, which is mentioned in this research as access possibility constraint. This constraint sets whether a vehicle can possibly move from one node to another in a particular network, or not.

3.3 The Mathematical Model

This section consists of detailed problem description of the disaster debris collection operation which is developed in this research and followed by problem formulation.

3.3.1 Problem Description

The CARP can be defined on an undirected graph $G = (V, A)$, in which V is the set of nodes and A is the set of arcs. The set A is partitioned into a subset of required arcs A_1, which must be serviced, and another subset of arcs A_2 required to maintain connectivity. Each required arc $a \in A_1$ is associated with a demand $z(a)$, a travel cost $tc(a)$ which refers to travelled distance, and a service cost $sc(a)$. The other arcs, in subset A_2, have a travel cost $tc(a)$ only. Usually, the service cost is greater than the travel cost because it takes more effort to service an arc than to only simply travel along it.

There exists a depot as a route starting point as well as a final destination point after all required arcs are completely serviced. In addition, intermediate depots can also be considered which serve as vehicles destination points to empty their loads. As soon as an arc or a road is serviced by the vehicle, it will open and can be used, without waiting until the vehicle which services it completes its route. In some practical cases, where roads are wide enough, the debris could be removed from the point to the road side. Considering that our objective is to collect the debris and open the blocked access, therefore the method whether to transport the debris to the intermediate depot or just removed it to the road side does not affect the progress. However in this paper, the roads are assumed to be quite narrow and to respect the capacity of vehicle and labor, it is assumed as necessary to transport the debris to the intermediate depot. The fixed cost for establishing such intermediate depot h is represented by G_h.

A set of identical vehicles K={1... m} is placed at the central depot node. Every vehicle has a fixed capacity Q_k and vehicle cost $F_k$which can be included in cost whenever the vehicle is used. Each vehicle serves a single route that must start and end at the depot. While doing so, vehicles can visit one of the intermediate depots whenever their loads exceed Q_k. As mentioned earlier, the vehicles are allowed to move from or to the adjacent arcs, whereas for distant arcs with blocked access, vehicles are not allowed to visit them before removing the blockage first (i.e., regulated by the access possibility constraint). This access possibility constraint belongs to the family of dynamic constraints, considering that the blocked access conditions in the entire network will immediately change every time a blockage is opened. The objective is to service all required arcs in the graph at least cost with feasible routes, where the cost is related to the number of vehicles used, the number of intermediate depots established, travel cost and the service cost.

3.3.2 Problem Formulation

A transformation from CARP in graph $G = (V, A)$ into an equivalent CVRP in a transformed graph $G' = (V', A')$ is performed. In a well-known transformation by Pearn et al. (1987), an arc $a \in A$ in CARP was represented by three nodes in the equivalent CVRP. Since anticipating large instance of disaster debris collection operation, the type of CARP transformation into CVRP with making two nodes for each required arc by Longo et al. (2006) will be used. In this transformation, an arc (i, j) in A_1 is associated with two nodes s_{ij} and s_{ji}, thus the resulting CVRP instance is defined on a complete undirected graph $G' = (V', A')$, where:

$$V' = \bigcup_{(i,j)\in A} \{s_{ij}, s_{ji}\} \cup \{o\} \tag{1a}$$

Node o serves as the depot. The cost involved here is only travel cost (tc) since service cost (sc) is not considered. The arc costs (c) and the demands (z) are defined as follows:

$$c_{s_{ij}s_{kl}} = \begin{cases} 0 & if\ i = k\ and\ j = l \\ c_{ij} & if\ i = l\ and\ j = k \\ d(i,k) & if\ i \neq k \neq l\ or\ j \neq l \neq k \end{cases} \tag{1b}$$

$$c_{o\, s_{ij}} = d(\mathrm{o}, i)$$

Here $d(i,j)$is the value of the shortest path from node i to node j in the CARP graph $G = (V, A)$. The new demands are:

$$z_{s_{ij}} = z_{s_{ji}} = \frac{1}{2} z(i,j) \tag{1c}$$

To better understand the transformation process; let us see an illustration in **Figure 3.1** and **Figure 3.2** which are taken from Longo et al. (2006).

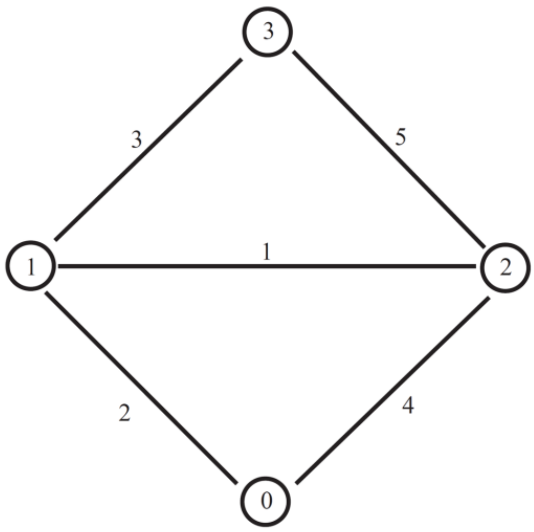

Figure 3.1 Original CARP graph

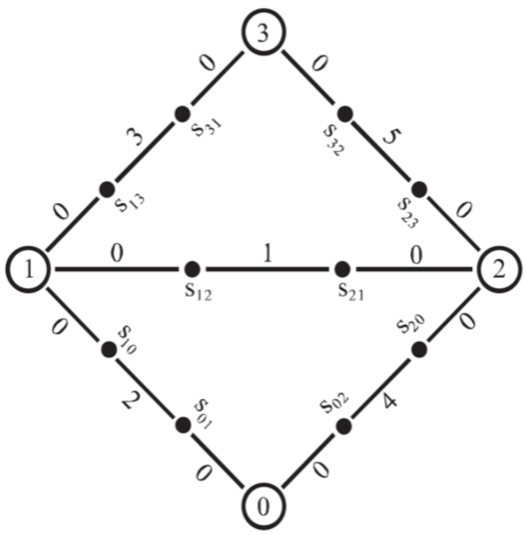

Figure 3.2 Transformed CVRP graph

The transformation fixes the flow variable (x_{ij}^{k}) on all undirected arcs $\{(s_{ij}, s_{ji}) \in A' \mid (i,j) \in A\}$ to 1. It means that CVRP solutions are only feasible where pairs of nodes s_{ij} and s_{ji} are visited in sequence, either s_{ij} from or to s_{ji}. It could be said that sum of z on s_{ij} and s_{ji} is a single quantity because they were obtained from the same single arc. As the impact, the vehicle must have sufficient load capacity to service pair of nodes s_{ij} and s_{ji} simultaneously, otherwise, vehicle must visit one of the intermediate depots to empty the load or look for other pair of nodes. After the above mentioned transformation applied on disaster debris collection operation problem, a CVRP with blocked access is obtained.

Notations used in this research are mostly the same as it was in Tagmouti et al. (2007), where $N' \subset V'$, is the set of required nodes that must be serviced. The depot is a single node, however it is also duplicated into an origin depot *o* and a destination depot *d* in *V'*. In addition, there exists a set of potentials intermediate depots$I = \{V'_{n+1.....}\}$, where $I \subset V'$and$n$ is the number of node that must be serviced. Even though the best location among a set of potential intermediate depots will be chosen, however one of the intermediate depot is always established right at the depot location because of the efficiency reason. This situation is acceptable in condition where it is difficult to provide an empty space in a particular area to establish other intermediate depots. Therefore, the depot will be also duplicated into an intermediate depot V'_{n+1}in *V'*. Once load of vehicles exceed Q_k, vehicles can choose one of the intermediate depots to empty the load. At the last tour, when all required nodes have completely serviced, vehicles must return to the depot.

The operation of multiple vehicles will increase cost due to fixed cost (F_k) of every additional vehicle. Moreover, operating multiple vehicles may not decrease total travel cost (*tc*), considering that working in a network with blocked access imposes the condition that routes must be operated in a particular sequence. Technically, every time a vehicle completed service on one node, it will update information of the access possibility to all other vehicles. Therefore, operating multiple vehicles will still be tested in this research, because some vehicles with varying routes which start simultaneously may decrease total required time (*tt*). Such operation can be applied to solve disaster debris collection problem with time restriction, such as depot closing time or time windows at the demand nodes. It should be noted that the classical CVRP itself can be considered a single vehicle routing operation without any time constraints as demonstrated in detail in Yang et al. (2000).

As a new idea for the disaster debris collection operation, an access possibility constraint is introduced on the nodes, which is represented by $p_{ij}^{k}, i \in V', j \in V', k \in K$, which is equal to 1 if vehicle k from node i can possibly visit or service node j, 0 otherwise. The access possibility matrix is always changed from original and previous positions, every time a vehicle completed services a required node and every time a blockage is opened. Therefore it can be classified as a dynamic constraint. The transformed CVRP's decision variables are: (1) the binary flow variables on the arcs x_{ij}^{k}, $(i,j) \in A', k \in K$, which are equal to 1 if vehicle k travels from node i to service node j, 0 otherwise; (2) The binary intermediate depot variables $y_h, h \in I$which are equal to 1 if intermediate depot h is established, 0 otherwise; and (3) the non-negative variables Q_i^k, $i \in V'$ which specify the remaining capacity of vehicle k just after servicing node i. Note that Q_o^k=Q_k, $k \in K$;Q_h^k=Q_k, $k \in K, h \in I$; the internodes travel cost (c_{ij}) is based on the shortest distance $d(i,j)$ of equation (1b), which in turn depends on travel cost $tc(i,j)$ and service cost $sc(i,j)$ of arc (i,j). The demands at depot and intermediate depots are zero, i.e., $z_o = z_d = z_h = 0, h \in I$; the maximum number of vehicles is limited to number m; M is the maximum capacity of intermediate depot; and g is the maximum number of intermediate depots, which can be established. The transformed CVRP as also reported in Pramudita et al. (2012), can be formulated as follows:

Min

$$\sum_{k \in K} \sum_{(i,j) \in A'} c_{ij} x_{ij}^{k} + \sum_{h \in I} G_h y_h \tag{2a}$$

Subject to

$$\sum_{k \in K} \sum_{i \in N' \cup I \cup \{o\}} x_{ij}^{k} = 1 \quad ; j \in N' \tag{2b}$$

$$\sum_{k \in K} \sum_{j \in N'} x_{oj}^{k} \le m \tag{2c}$$

$$\sum_{h \in I} y_h \le g \tag{2d}$$

$$\sum_{j \in N' \cup \{d\}} x_{oj}^{k} = 1 \quad ; k \in K \tag{2e}$$

$$\sum_{j \in N' \cup \{d\}} x_{ij}^{k} - \sum_{j \in N' \cup \{o\}} x_{ji}^{k} = 0 \quad ; k \in K, i \in N' \tag{2f}$$

$$\sum_{i \in N' \cup \{o\}} x_{id}^{k} = 1 \quad ; k \in K \tag{2g}$$

$$\sum_{j \in N'} z_j e_{hj} = q_h y_h \quad ; h \in I \tag{2h}$$

$$q_h y_h \leq M \quad ; h \in I \tag{2i}$$

$$x_{ij}^{k}\left(Q_i^k - z_j - Q_j^k\right) \geq 0 \quad ; (i,j) \in A', k \in K \tag{2j}$$

$$x_{ij}^{k} - p_{ij}^{k} \leq 0 \quad ; i \in V', j \in V', k \in K \tag{2k}$$

$$x_{jh}^{k} - y_h \leq 0 \quad ; h \in I, j \in N', k \in K \tag{2l}$$

$$0 \leq Q_i^k \leq Q_k \quad ; k \in K, i \in V' \tag{2m}$$

$$x_{ij}^{k} \in \{0,1\} \quad ; (i,j) \in A', k \in K \tag{2n}$$

$$p_{ij}^{k} \in \{0,1\} \quad ; i \in V', j \in V', k \in K \tag{2o}$$

$$y_h \in \{0,1\} \quad ; h \in I \tag{2p}$$

$$e_{hj} \in \{0,1\} \quad ; h \in I, j \in N' \tag{2q}$$

The objective function (2a) minimizes the sum of travel cost (*tc*) which refers to traveled distance; and the sum of cost of establishing intermediate depots. Instead of travel cost travel time can also be considered in the objective function if one wants to minimize the sum of total travel and service time (i.e., the total operation time) instead of total cost. The fixed vehicle cost (F_k) can also be added to all out going vehicles from depot $o \in V'$ if one wants to penalize the use of an additional vehicle. Constraint (2b) requires that each node in N' must be serviced once. Constraint (2c) is for maximum number of vehicles used. Constraint (2d) is for maximum number of intermediate depots established. Constraint (2e)-(2g) are the flow conservation constraints. Constraint (2h) is demands allocation to intermediate depots. Constraint (2i) is maximum capacity for the intermediate depot established (in our case set as infinity). Constraint (2j) ensures that vehicles are allowed to move from node i to node j only if the remaining capacity after servicing node i is still feasible to load demand in node j. Constraint (2k) ensures that vehicles are allowed to move from node i to node j only if the access between node i and node j is opened, i.e., p_{ij}^{k}=1. Constraint (2l) ensures that vehicles are allowed to move from node i to intermediate depot h to dispose the debris only if intermediate depot h is already established, i.e., y_h=1. Constraint (2m) ensures load values that do not exceed Q_k and are positive. Constraint (2n) is for binary values for the flow variables. Constraint (2o) is for binary values for access possibility. Constraint (2p) is for binary values for establishing intermediate depots. Constraint (2q) is binary values for allocating demands to the intermediate depots.

3.4 Meta-heuristics Solution Technique

This section is concerned with tabu search as a proposed meta-heuristics solution technique to solve the disaster debris collection operation as well as the performance validation of the algorithm by comparing the results with benchmark of Solomon (1987).

3.4.1 Tabu Search Algorithm

In this research, a tabu search meta-heuristics is proposed to solve the underlying CVRP to our disaster debris collection operation, as tabu search or heuristics in general are practically more appropriate and faster to solve large instances. Tabu search has quickly become one of the best and most widespread local search methods for combinatorial optimization. The tabu search scheme that proposed here is well documented in the literature by Gendreau (2003); Mastrolilli (2001); Cordeau et al. (2001); Hertz et al. (2000); and Augerat et al. (1998). The method performs an exploration of the solution area in a subset of the neighborhood $N(s)$ by moving from a solution s at iteration k to the best solution s' at iteration $k+1$. Since s' at iteration $k+1$ does not always have an improvement upon s at iteration k, a tabu mechanism is implemented to prevent the process from cycling over a sequence of solutions. The prohibited moves are kept in the list called as tabu list $T(s,k)$. Aspiration criteria $A(s,k)$ is set as an exception, which says even though some moves are tabu, however as long as there is an improvement in the solution, then the tabu list can be violated. **Figure 3.3** shows the basic algorithm of tabu search that is reviewed in Mastrolilli (2001).

3.4.2 Performance Validation of the Algorithm

In order to assess the accuracy of the tabu search algorithm more conclusively, we performed a computational experiment on a set of benchmark problems and compared the result with best known solutions for the 25, 50 and 100 customer instances of Solomon's Vehicle Routing Problem with Time Windows (VRPTW) benchmark problems (Solomon, 1987). The algorithm described above was coded in MATLAB R2010b and compiled on a

$s = s \rightarrow k = 1$.
Generate initial solution
WHILE the stopping condition is not met **DO**
  Identify $N(s)$. (Neighborhood set)
  Identify $T(s,k)$. (Tabu set)
  Identify $A(s,k)$. (Aspiration set)
  Choose the best $s' \in N(s,k) = \{N(s) - T(s,k)\}+A(s,k)$.
  Memorize s' if it improves the previous best solution
  $s = s' \rightarrow k = k+1$.
END WHILE

Figure 3.3 Basic tabu search algorithms

Table 3.1 Tabu search's result vs. Solomon's best known solution

No	Problem	Average Gap (%)	Average CPU time (s)
1	25 customers - C	0.57%	120.31
2	25 customers - R	0.65%	34.20
3	25 customers - RC	0.87%	66.38
4	50 customers - C	2.42%	641.76
5	50 customers - R	1.37%	398.40
6	50 customers - RC	5.14%	621.78
7	100 customers - C	4.81%	3839.98
8	100 customers - R	4.39%	1053.50
9	100 customers - RC	6.52%	3062.02

2666 MHz Genuine Intel processor x86 Family 6 Model 15 Stepping 11 with 2 GB of RAM under the Windows 7 Professional OS. Some modifications were needed in the proposed tabu search algorithm since the Solomon's VRPTW problems are typically different from our problem, firstly by setting all p_{ij}^k to be 1 (i.e., all links were opened or no blocked access exists), and secondly by applying time windows. After solving the Solomon's VRPTW problems using our tabu search, the obtained results were tabulated as **Table 3.1**; it gives the average performance of our tabu search meta-heuristics for various benchmark problems of the Solomon's VRPTW problems.

Most of the Solomon's VRPTW problems consisting of 25 customers were solved by the tabu search within reasonable time and with relatively small optimality gap. The average optimality gap of problems type C tested was 0.57 %, and for tested problems of type R and type RC the optimality gap was 0.65 % and 0.87 %, respectively, while the average optimality gap for all 25 customer instances tested was about 0.70 %. Some Solomon's VRPTW problems consisting of 50 and 100 customers were also solved by the tabu search.

The average optimality gap for 50 customer instances was 2.85 % and for 100 customer instances was 5.24 %. In light of this computational experiment it can be concluded that the designed tabu search heuristics has sufficient efficiency. This may also be noted that the tabu search meta-heuristics is designed for non-time windows. Therefore even a better performance is expected for the disaster debris collection operation.

3.5 Summary

A mathematical model is a description of a system using mathematical concepts and language. The process of developing a mathematical model is termed mathematical modeling. A model may help to explain a system and to study the effects of different components, and to make predictions about behavior.

As a basic idea in the mathematical model of disaster debris collection operation is that the new model proposed in this research is a modification of the classical model of Capacitated Arc Routing Problem (CARP). A modification in classical CARP is therefore, required to solve this kind of problem i.e., by adding a new constraint, which is mentioned in this research as access possibility constraint. This constraint sets whether a vehicle can possibly move from one node to another in a particular network, or not.

The CARP can be defined on an undirected graph $G = (V, A)$, in which V is the set of nodes and A is the set of arcs. The set A is partitioned into a subset of required arcs $A1$, which must be serviced, and another subset of arcs $A2$ required to maintain connectivity. Each required arc $a \in A1$ is associated with a demand $z(a)$, a travel cost $tc(a)$ which refers to travelled distance, and a service cost $sc(a)$. The other arcs, in subset $A2$, have a travel cost $tc(a)$ only. The fixed cost for establishing such intermediate depot h is represented by G_h.

A set of identical vehicles K={1... m} is placed at the central depot node. Every vehicle has a fixed capacity Q_k and vehicle cost F_k which can be included in cost whenever the vehicle is used. Each vehicle serves a single route that must start and end at the depot. While doing so, vehicles can visit one of the intermediate depots whenever their loads exceed Q_k. A transformation from CARP in graph $G = (V, A)$ into an equivalent CVRP in a transformed graph $G' = (V', A')$ is performed. As a new idea for the disaster debris collection operation, an access possibility constraint is introduced on the nodes, which is represented by $p_{ij}^k, i \in V',\ j \in V',\ k \in K,$ which is equal to 1 if vehicle k from node i can possibly visit or service node j, 0 otherwise. The access possibility matrix is always changed from original and previous positions, every time a vehicle completed services a required node and every time a blockage is opened. Therefore it can be classified as a dynamic constraint. The transformed CVRP can be formulated into equations, which consist of one objective function and fifteens constraints (Pramudita et al., 2012).

In this research, a tabu search meta-heuristics is proposed to solve the underlying CVRP to our disaster debris collection operation, as tabu search or heuristics in general are practically more appropriate and faster to solve large instances. In order to assess the accuracy of the tabu search algorithm more conclusively, we performed a computational experiment on a set of benchmark problems and compared the result with best known solutions for the 25, 50 and 100 customer instances of Solomon's Vehicle Routing Problem with Time Windows (VRPTW) benchmark problems (Solomon, 1987).

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Chapter 4

The Hypothesis Testing

4.1 Introduction

A research hypothesis is the statement created by researchers when they speculate upon the outcome of a research or experiment. Every true experimental design must have this statement at the core of its structure, as the ultimate aim of any experiment. The hypothesis is generated via a number of means, but is usually the result of a process of inductive reasoning where observations lead to the formation of a theory. Scientists then use a large battery of deductive methods to arrive at a hypothesis that is testable, falsifiable and realistic. The precursor to a hypothesis is a research problem, usually framed as a question. It might ask what, or why, something is happening. (Shuttleworth, 2008)

In order to make rational decisions about the reality of the model formulated, hypothesis tests are performed. It is done by creating a problem instances with artificial network, as reviewed in the next section.

4.2 Results on Hypothetical Test Instance

Before applying the formulation of the disaster debris collection problem (i.e., its underlying modified CVRP) on the realistic case study of Tokyo Metropolitan Area, the model formulation is tested on a small problem instance, which was also reviewed in Pramudita et al. (2012)

4.2.1 Single Intermediate Depot and Single Vehicle

A hypothetical test instance with 6 nodes (node no.1 is a depot) and 9 arcs (all are required arcs) was developed (**Figure 4.1**), where:

- V={1, 2, 3, 4, 5, 6};
- Q_k=20 ton;
- Travel Cost $tc(i,j)$: $tc(1,2)$=8, $tc(1,4)$=3, $tc(2,3)$=7, $tc(2,4)$=6, $tc(3,4)$=4, $tc(3,5)$=5, $tc(3,6)$=5, $tc(4,5)$=4, $tc(5,6)$=6;

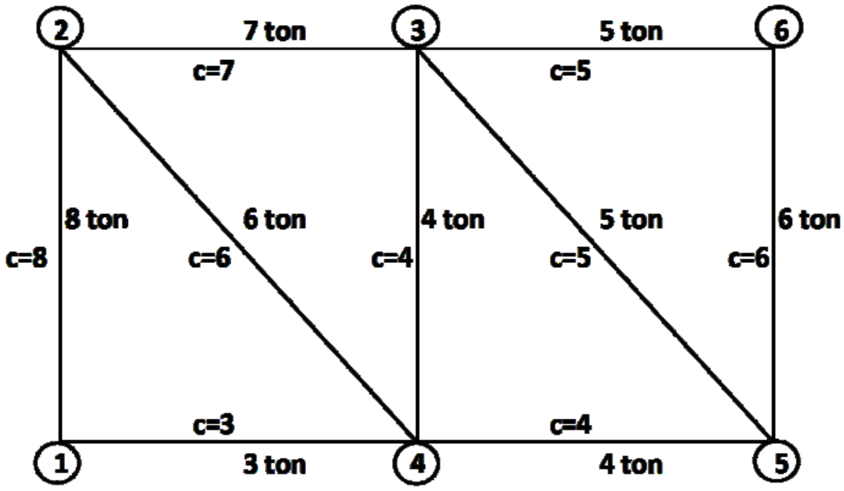

Figure 4.1 Capacitated Arc Routing Problem (CARP) test instance

- Demand $z(i,j)$: $z(1,2)$=8 ton, $z(1,4)$=3 ton, $z(2,3)$=7 ton, $z(2,4)$=6 ton, $z(3,4)$=4 ton, $z(3,5)$=5 ton, $z(3,6)$=5 ton, $z(4,5)$=4 ton, $z(5,6)$=6 ton;
- sc=0 and F_k=0, thus c=tc.

In the test instance, the service cost (sc), the fixed vehicle cost (F_k) and also cost of establishing an intermediate depot (G_h) have been assumed as 0, thus the cost involved is only the travel cost (tc) (i.e., $c_{ij} = tc_{ij}$). The service cost can be taken into consideration by assuming that sc is included in tc. In our case, the objective is to service all required nodes, and due the fact that the considered disaster debris collection operation is not time constrained, therefore the amount of service cost is always fixed and it will not affect the optimization process. Similarly, as mentioned earlier the fixed cost of a vehicle can be added to all outgoing arcs from the origin depot but for this particular test instance just a single vehicle is considered.

Establishing intermediate depots in a real life disaster problem is more likely classified in the area of politics, thus in the test instances, the intermediate depots are assumed to be pre-located at zero cost. However, G_h is still considered in the formulation, because to avoid perceptions that the intermediate depots could be established as many as possible and to keep the general form of the formulation so that this formulation can also be applied on the more complex problems in the future research. Another assumption taken in this case is that the shortest path from node i to node j in graph is the only path that exists for every node pair. Accordingly, the connection between i and j depends on whether $d(i,j)$is blocked or not, however if j is depot or intermediate depot, the vehicle always can move from i to j through the shortest path.

The CARP graph of test instance in **Figure 4.1** is transformed into the corresponding CVRP graph as shown in **Figure 4.2**, with number of nodes $V' = 2n + 1 + n'$; n is the number of arcs and n' is the number of intermediate depot. After transformation, the graph turns into a CVRP with number of nodes V'=20. Node no.1 still serves as depot; as well as duplicated into node no.20, which serves as the intermediate depot. The transformation introduces nodes $s_{ij}$and s_{ji} for all required arcs $(i,j)\in A$, where:

- V'={1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20};
- Q_k =20 ton;
- As calculated by the equation (1c), new demandsz_i : z_2=4 ton, z_3=1.5 ton, z_4=4 ton, z_5=3.5 ton, z_6=3 ton, z_7=3.5 ton, z_8=2 ton, z_9=2.5 ton, z_{10}=2.5 ton, z_{11}=1.5 ton, z_{12}=3 ton, z_{13}=2 ton, z_{14}=2 ton, z_{15}=2.5 ton, z_{16}=2 ton, z_{17}=3 ton, z_{18}=2.5 ton, z_{19}=3 ton.

The final transformed instance, a constrained CVRP instance with 20 nodes, is defined over a complete graph where the travel cost c_{ij} between nodes is calculated by the equation (1b) and presented in **Table 4.1**.

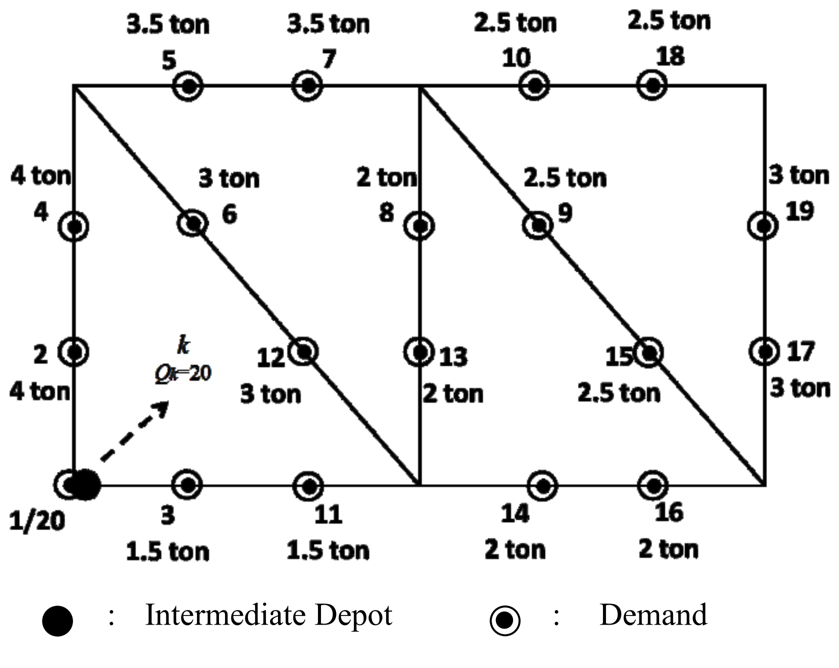

Figure 4.2 Transformed test instance in Capacitated Vehicle Routing Problem (CVRP)

Table 4.1 Travel cost matrix of CVRP

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0
2	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0
3	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0
4	8	8	8	0	0	0	7	7	7	7	6	6	6	6	10	10	10	12	12	8
5	8	8	8	0	0	0	7	7	7	7	6	6	6	6	10	10	10	12	12	8
6	8	8	8	0	0	0	7	7	7	7	6	6	6	6	10	10	10	12	12	8
7	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7
8	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7
9	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7
10	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7
11	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3
12	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3
13	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3
14	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3
15	7	7	7	10	10	10	5	5	5	5	4	4	4	4	0	0	0	6	6	7
16	7	7	7	10	10	10	5	5	5	5	4	4	4	4	0	0	0	6	6	7
17	7	7	7	10	10	10	5	5	5	5	4	4	4	4	0	0	0	6	6	7
18	12	12	12	12	12	12	5	5	5	5	9	9	9	9	6	6	6	0	0	12
19	12	12	12	12	12	12	5	5	5	5	9	9	9	9	6	6	6	0	0	12
20	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0

The process starts by finding an initial solution using a greedy heuristics. This technique attempts to construct a feasible solution that is moving from the current point. The idea is fairly simple; starting from the depot, a vehicle chooses the closest demand node until all required nodes are visited. The vehicle returns to the depot at the end of its tour, however, it may also visit one of the established intermediate depots, whenever its load exceeds the capacity. The objective value of total travel cost (tc) obtained is 93 with route 1 – 3 – 11 – 13 – 8 – 9 – 15 – 17 – 19 – 20 – 2 – 4 – 6 – 12 – 14 – 16 – 20 – 7 – 5 – 10 – 18 – 1. Then, tabu search was used to find a better solution than the initial solution and finally the best solution was found with a total travel cost(tc) of 69 and with route 1 – 3 – 11 – 13 – 8 – 10 – 18 – 19 – 17 – 20 – 2 – 4 – 6 – 12 – 20 – 14 – 16 – 15 – 9 – 7 – 5 – 1.

The new idea proposed in this research is an access possibility constraint represented by p_{ij}^{k}which controls whether the vehicle can possibly move from one node to another, or not. If vehicle k wants to move from i to j, node i and j must be either adjacent; or blocked nodes between node i and j must be serviced by vehicle k first or are already serviced by other vehicles. This constraint belongs to the family of dynamic constraints, considering that the blocked access structure in the entire network will immediately change every time a blockage is opened. To better understand how it works let's see the access possibility matrix in **Table 4.2**, **4.3** and **4.4** at various stages of the solution.

Table 4.2 Access possibility matrix (Stage 1)

	1/20	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1/20	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
4	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
6	1	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0
7	1	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0
8	1	0	0	0	0	0	1	1	1	1	0	0	1	0	0	0	0	0	0
9	1	0	0	0	0	0	1	1	1	1	0	0	0	0	1	0	0	0	0
10	1	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1	0
11	1	0	1	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
12	1	0	0	0	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0
13	1	0	0	0	0	0	0	1	0	0	1	1	1	1	0	0	0	0	0
14	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	0	0	0
15	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0
16	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
18	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
19	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1

Table 4.3 Access possibility matrix (Stage 2)

	1/20	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1/20	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
2	1	1	1	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
3	1	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
4	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
6	1	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0
7	1	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0
8	1	0	0	0	0	0	1	1	1	1	0	0	1	0	0	0	0	0	0
9	1	0	0	0	0	0	1	1	1	1	0	0	0	0	1	0	0	0	0
10	1	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1	0
11	1	1	1	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
12	1	0	0	0	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0
13	1	0	0	0	0	0	0	1	0	0	1	1	1	1	0	0	0	0	0
14	1	0	0	0	0	0	0	0	0	0	1	1	1	1	0	1	0	0	0
15	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0
16	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
18	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
19	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1

Table 4.4 Access possibility matrix (Stage 3)

	1/20	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
1/20	1	1	1	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
2	1	1	1	1	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
3	1	1	1	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
4	1	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
6	1	0	0	1	1	1	0	0	0	0	0	1	0	0	0	0	0	0	0
7	1	0	0	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0
8	1	0	0	0	0	0	1	1	1	1	0	0	1	0	0	0	0	0	0
9	1	0	0	0	0	0	1	1	1	1	0	0	0	0	1	0	0	0	0
10	1	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	1	0
11	1	0	1	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
12	1	1	1	0	0	1	0	0	0	0	1	1	1	1	0	0	0	0	0
13	1	1	1	0	0	0	0	1	0	0	1	1	1	1	0	0	0	0	0
14	1	1	1	0	0	0	0	0	0	0	1	1	1	1	0	1	0	0	0
15	1	0	0	0	0	0	0	0	1	0	0	0	0	0	1	1	1	0	0
16	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0
17	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1
18	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
19	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1

In stage 1, when vehicle is still at node no.1 or depot & its tour has not yet started, the access possibility conditions are as follows; (i) Only if i and j are adjacent nodes, the vehicle can move from i to j and vice versa, such as 1-1, 1-2, 1-3, etc., which is shown by p_{ij}^{k}=1 which means that the accesses are opened; and (ii) If j is intermediate depot, the vehicle always can move from i to j through the shortest path. In stage 2, after vehicle moved from node 1 to node 3, the blocked access structure in the entire network is changed. It can be seen as the change of p_{ij}^{k}=1 at 1-11, 2-11, etc. Then in stage 3, after vehicle moved from node 3 to node 11, the matrix of access possibility is changed again, which can be seen as the change of p_{ij}^{k}=1 at 1-12, 1-13, 1-14, 2-12, 2-13, 2-14, 3-12, 3-13, 3-14, etc. This change process of the matrix of access possibility continues until the vehicle ends its tour and returns to the depot.

4.2.2 Multi Intermediate Depots and Single Vehicle

The problem in section **4.2.2** is the same as it in section **4.2.1**, except on the additional intermediate depots at node no.21, as shown in **Figure 4.3**; and the travel cost c_{ij} between nodes is presented in **Table 4.5**.

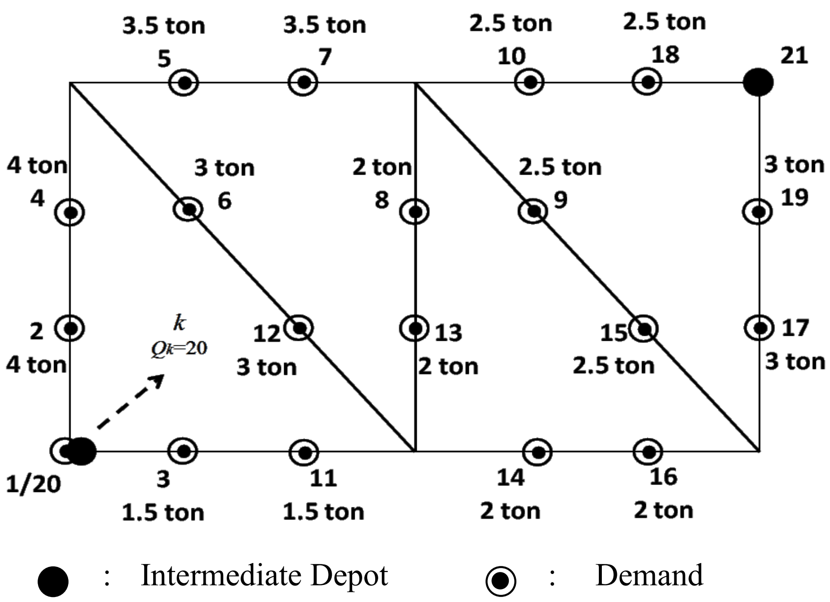

Figure 4.3 CVRP with 2 intermediate depots

Table 4.5 Travel cost matrix of CVRP (2 intermediate depots)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0	12
2	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0	12
3	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0	12
4	8	8	8	0	0	0	7	7	7	7	6	6	6	6	10	10	10	12	12	8	12
5	8	8	8	0	0	0	7	7	7	7	6	6	6	6	10	10	10	12	12	8	12
6	8	8	8	0	0	0	7	7	7	7	6	6	6	6	10	10	10	12	12	8	12
7	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7	5
8	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7	5
9	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7	5
10	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7	5
11	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3	9
12	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3	9
13	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3	9
14	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3	9
15	7	7	7	10	10	10	5	5	5	5	4	4	4	4	0	0	0	6	6	7	6
16	7	7	7	10	10	10	5	5	5	5	4	4	4	4	0	0	0	6	6	7	6
17	7	7	7	10	10	10	5	5	5	5	4	4	4	4	0	0	0	6	6	7	6
18	12	12	12	12	12	12	5	5	5	5	9	9	9	9	6	6	6	0	0	12	0
19	12	12	12	12	12	12	5	5	5	5	9	9	9	9	6	6	6	0	0	12	0
20	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0	12
21	12	12	12	12	12	12	5	5	5	5	9	9	9	9	6	6	6	0	0	12	0

By using tabu search heuristics, total *tc* obtained in the test instance is 63 and the route is 1 – 3 – 11 – 14 – 16 – 15 – 9 – 10 – 18 – 21 – 19 – 17 – 12 – 6 – 4 – 2 – 20 – 13 – 8 – 7 – 5 – 1. Total *tc* in section **4.2.2** decrease if compared to it in section **4.2.1** because vehicle has more than 1 intermediate depot as destination points to empty the load once it exceed Q_k. Based on the results obtained from problem in section **4.2.1** and **4.2.2**, a comparison of total *tc* obtained between single and multi-intermediate depot is presented in **Table 4.6**.

Table 4.6 Comparison of single and multi-intermediate depots

No	Type of Problem	∑ Vehicle	*ID Node	Travel Cost *(distance units)*
1	Single *ID	1 *Qk*=20	20	69
2	Multiple *IDs	1 *Qk*=20	20 & 21	63

*ID=Intermediate Depot

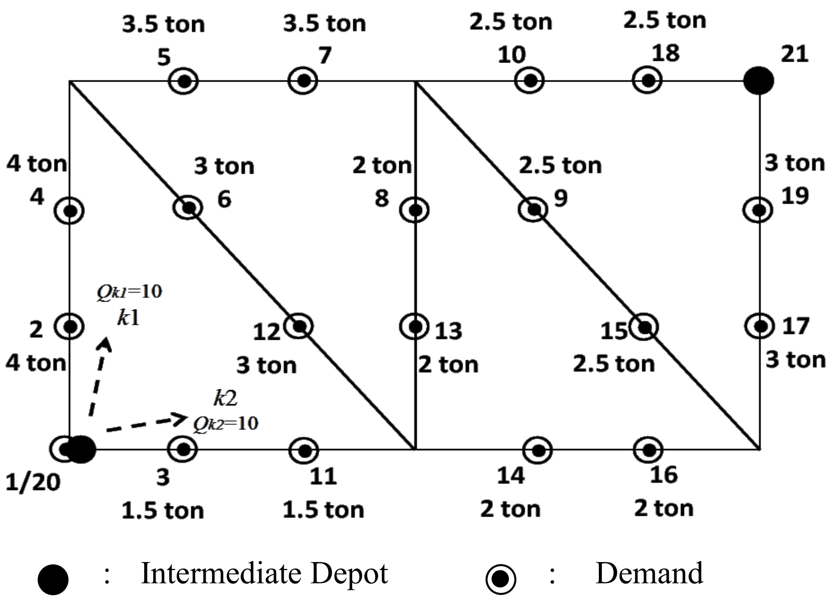

Figure 4.4 CVRP with 2 intermediate depots and 2 vehicles

Besides its effect on total tc, adding the number of intermediate depots will also affect other components of cost, since establishing intermediate depots have consequent fixed cost G_h. So if we want to make the best total cost, it need to be compared whether decrease in total tc balances increase in total G_h, or vice versa. But for a particular reason, as mentioned before, G_h in this problem instance is assumed to be 0.

4.2.3 Multi Intermediate Depots and Multi Vehicles

The problem in section **4.2.3** is the same as it in section **4.2.2**, except on the number of vehicle used and Q_k. We operate two identical vehicles $k1$ and $k2$ with Q_k=10 ton each, as shown in **Figure 4.4**.

Table 4.7 Comparison of single and multi-vehicles

No	Type of Problem	∑ Vehicle	*ID Node	Travel Cost *(distance units)*	Required Time *(time units)*
1	Single Vehicle	1 *Qk*=20	20 & 21	63	63
2	Multiple Vehicles	2 @*Qk*=10	20 & 21	95	48

*ID=Intermediate Depot

Here, we consider operating two vehicles, so that both of them can start moving from depot simultaneously on to the two different accesses or arcs incident to the depot. It can be noticed that once these accesses are opened, additional vehicles can also move out of depot too. However, the number of vehicles is limited to two only. Then each vehicle starts moving from depot simultaneously but to different accesses or arcs.

By using tabu search heuristics, total tc obtained in the test instance is 95, respectively by $k1$ is 48 with route 1 – 2 – 4 – 20 – 13 – 8 – 10 – 18 – 21 – 7 – 5 – 1 and by $k2$ is 47 with route 1 – 3 – 11 – 12 – 6 – 20 – 14 – 16 – 17 – 19 – 21 – 9 – 15 – 1. Total tc using multi-vehicles as in section **4.2.3** seems not less than total tc using single vehicle as in section **4.2.2**, so it can be said that adding the number of vehicle will not necessarily reduce total tc. The explanation is $k1$ and $k2$ moving simultaneously, so the possibility access to be traversed is relative low reminding that still many accesses blocked by debris. In case where fixed cost F_k is considered, we need to balance the saving in tc with additional cost caused by F_k. Interesting finding is when we change the unit distance cost into unit time, which in this case is changing tc into tt. There is a saving in total tt if the operation is done using two vehicles. It appears that total tt in section **4.2.2** is 63, while the total tt in section **4.2.3** is 48. Based on the results obtained from problem in section **4.2.2** and **4.2.3**, a comparison of total tc and total tt between single and multi-vehicles is presented in **Table 4.7**.

4.2.4 The Best Location of Intermediate Depot

In the test instance, the service cost (sc) and the fixed vehicle cost (F_k) have been assumed as 0, thus the cost involved is only the travel cost (tc) (i.e.,c_{ij}=$tc_{ij} + G_h$). In our case, the objective is to service all required nodes, and due the fact that the considered disaster debris collection operation is not time constrained, therefore the amount of service cost is always fixed and it will not affect the optimization process. Similarly, as mentioned earlier the fixed cost of a vehicle can be added to all outgoing arcs from the origin depot but for this particular test instance just a single vehicle is considered. We attempt to find the best location to establish intermediate depots. By modifying the problem in b), let there are 6 possible candidate locations of intermediate depot, as shown in **Figure 4.5**; and the travel cost c_{ij} between nodes is presented in **Table 4.8**.

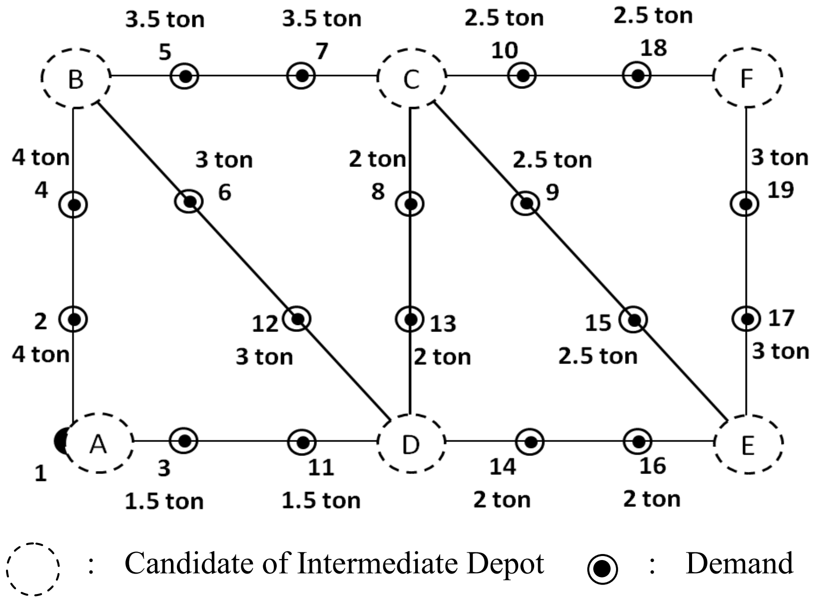

Figure 4.5 Candidate locations of intermediate depot

Table 4.8 Travel cost matrix of CVRP (multi intermediate depots)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	A	B	C	D	E	F
1	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0	8	7	3	7	12
2	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0	8	7	3	7	12
3	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0	8	7	3	7	12
4	8	8	8	0	0	0	7	7	7	7	6	6	6	6	10	10	10	12	12	8	0	7	6	10	12
5	8	8	8	0	0	0	7	7	7	7	6	6	6	6	10	10	10	12	12	8	0	7	6	10	12
6	8	8	8	0	0	0	7	7	7	7	6	6	6	6	10	10	10	12	12	8	0	7	6	10	12
7	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7	7	0	4	5	5
8	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7	7	0	4	5	5
9	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7	7	0	4	5	5
10	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7	7	0	4	5	5
11	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3	6	4	0	4	9
12	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3	6	4	0	4	9
13	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3	6	4	0	4	9
14	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3	6	4	0	4	9
15	7	7	7	10	10	10	5	5	5	5	4	4	4	4	0	0	0	6	6	7	10	5	4	0	6
16	7	7	7	10	10	10	5	5	5	5	4	4	4	4	0	0	0	6	6	7	10	5	4	0	6
17	7	7	7	10	10	10	5	5	5	5	4	4	4	4	0	0	0	6	6	7	10	5	4	0	6
18	12	12	12	12	12	12	5	5	5	5	9	9	9	9	6	6	6	0	0	12	12	5	9	6	0
19	12	12	12	12	12	12	5	5	5	5	9	9	9	9	6	6	6	0	0	12	12	5	9	6	0
A	0	0	0	8	8	8	7	7	7	7	3	3	3	3	7	7	7	12	12	0	8	7	3	7	12
B	8	8	8	0	0	0	7	7	7	7	6	6	6	6	10	10	10	12	12	8	0	7	6	10	12
C	7	7	7	7	7	7	0	0	0	0	4	4	4	4	5	5	5	5	5	7	7	0	4	5	5
D	3	3	3	6	6	6	4	4	4	4	0	0	0	0	4	4	4	9	9	3	6	4	0	4	9
E	7	7	7	10	10	10	5	5	5	5	4	4	4	4	0	0	0	6	6	7	10	5	4	0	6
F	12	12	12	12	12	12	5	5	5	5	9	9	9	9	6	6	6	0	0	12	12	5	9	6	0

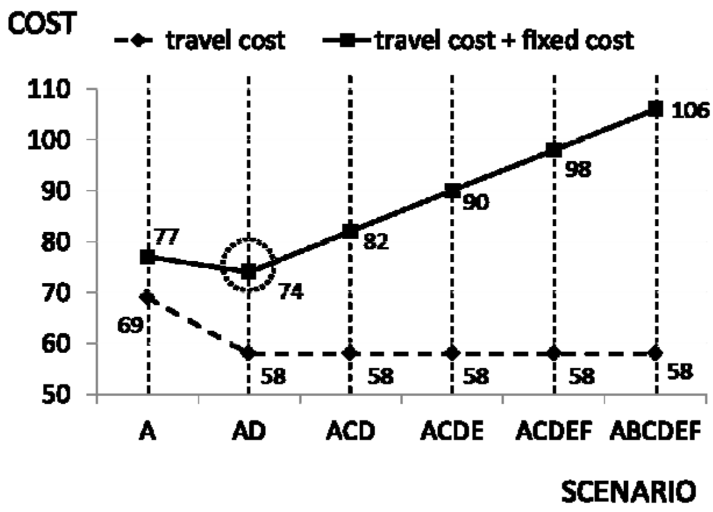

Figure 4.6 Solution for the best cost

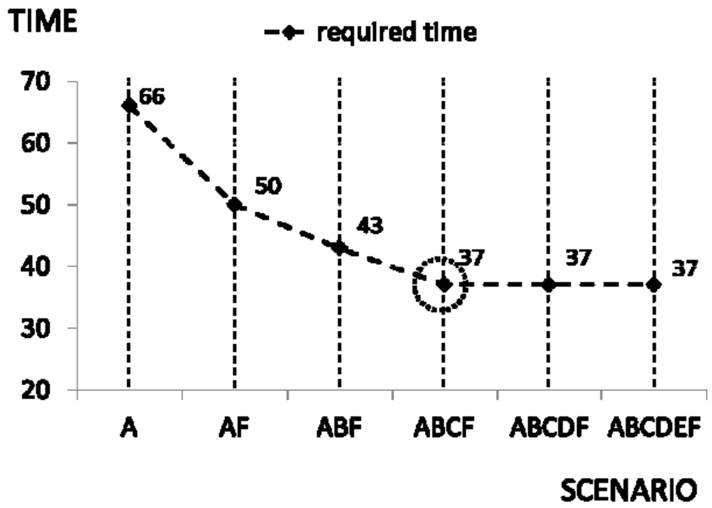

Figure 4.7 Solution for the best time

After transformation, the graph turns into L-CVRP with number of nodes V'=25, which consists of node no.1 as a depot), node no.2-19 as required nodes and node A-B-C-D-E-F as candidate locations of intermediate depot. The vehicle capacity (Q_k) is 20 ton, fixed intermediate depot cost (G_h) is 8as well as the travel cost c_{ij} between nodes is calculated by the equation (1b) and was also presented in Pramudita et al. (2012).

Figure 4.6 shows the best cost obtained from the best combination scenario of intermediate depot establishment for each possible number. The dashed line is travel costs (tc) only (without considering G_h), which shows the conditions of tc reduction from 69 to 58 when scenario AD is used (i.e., the second intermediate depot at node D is established besides the first one at node A). The subsequent intermediate depot establishments by others scenario do not affect the travel costs which are stagnant at the same amount. The solid line is travel costs (tc) aggregate with G_h, which shows that the optimum solution obtained when scenario AD is used, i.e., two intermediate depots established at node A (qi≥14 ton) and D (qi≥34 ton). The best total cost is 74 and with route 1/A – 3 – 11 – 14 – 16 – 15 – 9 – 7 – 5 – D – 13 – 8 – 10 – 18 – 19 – 17 – D – 12 – 6 – 4 – 2 – 1/A.

Similar to the previous figure, however **Figure 4.7** shows the best required time from the best combination scenario of intermediate depot establishment for each possible number. The next test instance is a modification of the earlier problem by operating multiple vehicles (i.e.,k_1 and k_2) are also given in Pramudita et al. (2012). As mentioned earlier in multiple vehicles operation the objective function minimizes total travel time ($\sum tt$) therefore F_k and G_h can still be ignored. As seen that the addition of a second intermediate depot until the fourth one affect reduction of tt significantly (i.e., 66 → 50 → 43 → 37), however next become stagnant. Therefore, the optimum solution obtained when scenario ABCF is used, i.e., four intermediate depots established at node A (qi≥15 ton), B (qi≥17 ton), C (qi≥7 ton) and F (qi≥9 ton). The best total required time (tt) is 37 and with routes $k1$: 1/A – 2 – 4 – B – 5 – 7 – C – 9 – 15 – 16 – 14 – 1/A and $k2$: 1/A – 3 – 11 – 12 – 6 – B – 13 – 8 – 10 – 18 – F – 19 – 17 – 1/A.

4.6 Summary

A research hypothesis is the statement created by researchers when they speculate upon the outcome of a research or experiment. In order to make rational decisions about the reality of the model formulated, hypothesis tests are performed. It is done by creating a problem instances with artificial network, as reviewed in the next section.

Before applying the formulation of the disaster debris collection problem (i.e., its underlying modified CVRP) on the realistic case study of Tokyo Metropolitan Area, the model formulation is tested on a small problem instance, which was also reviewed in Pramudita et al. (2012). A hypothetical test instance with 6 nodes (node no.1 is a depot) and 9 arcs (all are required arcs). After transformation, the graph turns into a CVRP with number of nodes V'=20. Node no.1 still serves as depot; as well as duplicated into node no.20, which serves as the intermediate depot.

The hypothetical test instance is performed into four scenarios i.e., (i) single intermediate depot and single vehicle; (ii) multi intermediate depots and single vehicle; (iii) multi intermediate depots and multi vehicles; and (iv) the best location of intermediate depot.

References

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Chapter 5

The Application on a Realistic Case Study of Tokyo Metropolitan Area

5.1 Introduction

An estimation procedure was established by Hirayama et al. (2010) to assess the amount of debris resulting from earthquake and flood disasters in Tokyo Metropolitan Area. It was shown that the procedure of disaster debris estimation in disaster management and operation systems could be established for not only emergency response in the aftermath, it can also be used in pre-disaster planning. In that case study, the amount of debris from earthquake and catastrophic flood disasters in Tokyo Metropolitan Area was estimated according to the hazard maps.

5.2 Data of Disaster Debris of Tokyo Metropolitan Area

The data of disaster debris used in this research is estimation data as result from the study of “Establishment of Disaster Debris Management Based on Quantitative Estimation Using Natural Hazard Maps” by Hirayama et al. (2010). In such study, an estimation procedure was established to assess the amount of debris resulting from earthquake and flood disasters. Per unit generation of earthquake disaster debris was examined on the basis of observed debris discharge from the 1995 Great Hanshin Awaji Earthquake and the 2004 Niigata Chuetsu Earthquake. In addition, the per unit generation of disaster debris from flood damage above floor level was estimated at 4.6 t/household. It was shown that this procedure would allow the amount of debris to be estimated in order that disaster management and operation systems could be established for not only emergency response in the aftermath but also pre-disaster planning. In a case study, the amount of disaster debris from earthquake and catastrophic flood disasters in the Tokyo Metropolitan Area was estimated according to hazard maps. The result of estimation data of disaster debris amount of Tokyo Metropolitan Area is then used as a realistic case of our research. The detailed method on how to obtain the estimation data of disaster debris can be reviewed in Hirayama et al. (2010). The example of the data provided by Hirayama (2010) is presented in **APPENDIX A-1**.

Based on the assessment of debris resulting from earthquake and flood disasters in Tokyo Metropolitan Area, the amount of debris information was spread over 5 by 5 grid areas or 25 grid areas of 261,506 square meters each. Since the data result is not detailed, therefore the amount of debris which is spread on every road in each grid area needs to be calculated. In this research, such calculation was performed by dividing the road area by the grid areas, and then multiplied by the sum of debris in corresponding grid area. In order to get data of road area, the road lengths are measured from existing Tokyo map; meanwhile the road widths are assumed as an average 3.25 m/lane and a total of 4 lanes were assumed for each road.

5.3 Results on Realistic Case Study

The Central Disaster Prevention Council in Hirayama et al. (2010), estimates damage from scenario earthquakes. First, from the household distribution of the Tokyo Metropolitan Area and the earthquake ground motion, the number of damaged houses was calculated based on the fragility function mentioned previously. According to the damage estimates, 241,873 houses suffered complete collapse and 1,388,147 houses sustained moderate collapse. Second, counter measures against catastrophic flood disasters in the Tokyo Metropolitan Area, and estimated the damage from flood disasters in the area. The inundation depth of the Tone River flood disaster has been calculated. According to estimations of damage from flood disasters, 631,547 houses would suffer damage beyond floor level inundation. It can be shown that as many as 247,491 houses in Adachi, Edogawa, and Katsushika wards on the coast of Tokyo Bay would be damaged. A period of inundation in these wards of more than three weeks was estimated. It may be assumed that damage to housing in the Tokyo Bay coast could be even more.

In this section, the model formulation of the disaster debris collection problem will be applied to solve the realistic case study which was assessed by Hirayama et al. (2010). In addition to that spatial and statistical data of Tokyo Metropolitan Area is also used based on Japanese Standard Grid Square and Grid Square Code used for the Statistics (Announcement No.143 by the Administrative Management Agency Japan, on July, 12, 1973) which can be reviewed in **APPENDIX A-2**. The position of Tokyo Metropolitan Area in Japan Area using the Japanese Standard Grid can be seen in **Figure 5.1**. Considering the large size of entire

Tokyo Metropolitan Area, the model formulation will be tested in two spot locations only, representing eastern and western part of Tokyo as shown in **Figure 5.2**.

5.3.1 Eastern Part of Tokyo Metropolitan Area

Location A, as shown in **Figure 5.3**, is an area of 6,537,657 square meters in eastern part of Tokyo (139°48′0″E - 139°49′53″E and 35°40′45″N - 35°42′0″N). It consists of 22 roads which are also treated as the required arcs in our model formulation.

After developing the graph transformation using the equation (1a), the location A area can also be treated as a CARP graph, as shown in **Figure 5.4**. Now the transformed CVRP graph consists of 46 nodes, as shown in **Figure 5.5**.

Node no.1 serves as depot, where vehicles start and end their tour; and the other nodes are debris collection points or the required nodes. The distances between these required nodes (c_{ij}) are calculated by the equation (1b). Besides serving as depot, node no.1 is duplicated into node no.46 which serves as the intermediate depot. Node no.1 or no.46 is designated as depot or intermediate depot since considering that there is a huge open space available (*to be named*) close to the location which could function as vehicle parking area as well as the disposal site. In this case, depot or intermediate depot is pre-located and not included in the optimization process.

The objective function of this operation is opening the blockage; therefore the debris could be removed from the road to a near vacant space, such as near the road side. However in this case, vehicles still need to load and transport some part of the debris to the disposal site due to the limited space and due to the assumption that some debris material cannot be left anyway in the public space. The assumption is that 50% of total amount of debris on the road needs to be loaded and transported to the disposal sites. It may be noted that the percentage figure (i.e., of 50%) is just an arbitrary assumption, since exact proportion may highly be dependent on specific site condition, the nature of debris and the urgency of debris removal operation.

In this research, because of lack of available data, another assumption is taken that all considered arcs are blocked due to the debris; or every arc is treated as a required arc. Therefore, as mentioned earlier in the test problem instances, p_{ij}^{k} sets that only adjacent arcs can be connected with each other, while for distant arcs it was assumed that there may be no way to connect them before removing the blocked access first. On the other hand, considering that there may some other roads besides the main road, therefore the accessibility regarding the p_{ij}^{k} constraint could be relaxed. In such case, one may modify p_{ij}^{k} that does not exactly restrict the access only to adjacent arcs at the initial stage. Such modification, applied on p_{ij}^{k} constraint; would suggest that as long as there exist other paths from node i to node j, vehicle k still can possibly move from node i to node j even though without traversing the blocked shortest path; however, in that case the available open path may not be the shortest path connecting the node i to node j. However in this case research, the p_{ij}^{k} constraint is set to a maximum closed state due to the lack of available data and due the ease factor of such assumption.

In the real life situations, demands (i.e., the amount of debris to be removed) in some arcs could very possibly exceed the vehicle capacity, so was the case also in this case study of Tokyo Metropolitan Area. Hence, in anticipating such situation, instead of a single vehicle some specified number of vehicles may be operated considering that they will work together in a group with the same route. Therefore, in this case research, it is assumed that there are 20 standard dump truck vehicles involved in this disaster debris collection operation with an individual capacity of 10 ton each. Furthermore, it is also assumed that those vehicles will be operated as one unit and thus will be treated as a single group of vehicles with unified capacity of 200 ton. In some cases, the number of vehicles could be reduced so that fixed vehicle cost may decrease. However as a consequence, the frequency of vehicles commuting to the disposal site to empty load as well as travel cost will increase. Even after assuming a reasonable size of a unit group of vehicles, still because of limited capacity, the group of vehicles may not necessarily be able to service a single arc completely without returning to intermediate depot to empty the load. This condition can give rise to additional costs, therefore, a fixed travel cost (tc') is also considered, besides *tc*. Here tc' is defined as the commuting cost of the group of vehicles from and to the nearest intermediate depot because of the limited capacity in servicing single required arc. If one wants to minimize the total travel time, tc' can also be changed into tt' (i.e., the total commuting travel time to and from an arc with a demand greater than the capacity of the group of vehicles), which will be referred as the fixed required time. The amount of the tc' can be calculated before the transformation from arcs into nodes with the equation as follows.

$$tc' = \sum_{(i,j)\in A_1} \min\left(2c_{hj}\left\lfloor\frac{z(i,j)}{Q_k}\right\rfloor\right);\ h \in I \tag{3a}$$

By considering the tc', it is assumed that the original demands $(z(i,j),(i,j) \in A_1)$ can be reduced until the amount equal or less than the capacity of group of vehicles $(z'(i,j) \leq Q_k,(i,j) \in A_1)$. Therefore the model formulation is optimized by considering that the remaining demands $(z'(i,j),(i,j) \in A_1)$ can be loaded by vehicle and then vehicle continues its tour to the other nodes without returning to intermediate depot if the capacity is still available. The amounts of remaining debris exist in each node or the remaining demands are presented in **APPENDIX B-1**.

$$z'(i,j) = z(i,j) - Q_k \left\lfloor \frac{z(i,j)}{Q_k} \right\rfloor \; ; \; (i,j) \in A_1 \tag{3b}$$

Similar to the test instance and due to the reasons discussed in earlier chapter the service cost (*sc*) is assumed to be zero here as well. Some fixed costs can be determined before running the optimization process i.e., total fixed vehicle cost (F_k) as well astotal fixed travel cost (*tc'*) which was calculated as 641,338 distance units. Subsequently, the total travel cost (*tc*) is calculated by applying the model formulation with the reduced demands; using tabu search, the best total travel cost (*tc*) is obtained as 45,933 distance units with route as shown in **Figure 5.6** and **APPENDIX B-2**.

5.3.2 Western Part of Tokyo Metropolitan Area

Location B, as shown in **Figure 5.7**, is an area of 6,537,657 square meters in western part of Tokyo (139°40′52″E - 139°42′45″E and 35°40′45″N - 35°42′0″N). It has more complicated road network structure than the eastern part, in terms of larger number of existing arcs i.e., 98 arcs, as shown in **Figure 5.8**.

The location B area can also be treated as a graph. After developing the graph transformation using the equation (1a), now the final transformed CVRP graph consists of 198 nodes, as shown in **Figure 5.9**.

Node no.1 serves as depot, and in case 1, it is duplicated into node no.198 which serves as an intermediate depot. Node no.1 or no.198 is located as depot or intermediate depot considering the fact that there is a huge open space (*to be named*) available close to the location. Similar to the location A, the amounts of remaining debris exist or the remaining demands in each node were calculated and are presented in **APPENDIX C-1**. In this case also, it is assumed that there are 20 standard dump truck vehicles involved in this operation with an individual capacity of 10 ton each working as a single group of vehicles with unified capacity of 200 ton. The total fixed travel cost (tc') was calculated as 5,934 distance units before running the optimization process. Subsequently, total travel cost (tc) is calculated by applying the model formulation; using tabu search, the best total travel cost (tc) obtained was 93,036 distance units with route as shown in **Figure 5.10** and **APPENDIX C-2**.

Because of the complexity of the road network structure in location B, another strategy is evaluated <u>in case 2</u> for location B, i.e., with establishing a second intermediate depot. Besides at node no.198, another intermediate depot was considered at node no.199 which is also close to a huge open space (*to be named*), as shown in **Figure 5.11**.

The total fixed travel cost (tc') was reduced to 3,398 distance units and the best total travel cost (tc) was also reduced to 57,970 distance units with route as shown in **Figure 5.12** and **APPENDIX C-3**. Therefore, availability of more intermediate depots (located strategically) would help in reducing the travel cost involved in disaster debris collection operation. The presence of two intermediate depots would make more options of destination points available for a vehicle to empty its load. A brief description of the results is presented in **Table 5.1**. However, if their establishment requires an establishment cost (G_h), it must be evaluated that such a decrease in total travel cost is still overall a cost saving or not. It may be noted that the model formulation (2a - 2n) is capable of handling this concern as well; the combination of disaster debris collection operation and location of intermediate depot(s) will be considered in future research.

<u>In case 3</u> along with the intermediate depots established at node no.198 and no.199, the problem is further modified by considering operation of multiple groups of vehicles. It means that all vehicles may not move together as a single unit; however it depends if the group is involved in disaster debris collection from a specific node with large enough demand.

Table 5.1 Comparison of single and multiple intermediate depots

No	Type of Problem	∑ Vehicle	*ID Node	Travel Cost *(distance units)*
1	Single *ID	1 *Qk*=200	198	98,970
2	Multiple *IDs	1 *Qk*=200	198 & 199	61,368

*ID=Intermediate Depot

Table 5.2 Comparison of single and multiple groups of vehicles

No	Type of Problem	∑ Vehicle	*ID Node	Travel Cost *(distance units)*	Required Time *(time units)*
1	Single Vehicle	1 *Qk*=200	198 & 199	61,368	61,368
2	Multiple Vehicles	4 @*Qk*=50	198 & 199	190,189	53,823

*ID=Intermediate Depot

Therefore in this operation, it is assumed that there are four groups of vehicles with capacity of 50 ton each and all may have varying routes. Since the capacity of vehicles is reduced, the remaining demands should be less than they were in the previous cases (case 1 and 2) in **APPENDIX C-1**.

As mentioned earlier, that multiple vehicles operation has the objective function to find the best required time (*tt*). Therefore, in order to deal with this kind of problem, the CVRP was optimized by considering the time of operation instead of travel distance. The total fixed required time (*tt'*) was obtained as 20,899 time units and the best total required time (*tt*) was found as 32,924 time units using the tabu search heuristics with routes for each vehicle group as shown in **APPENDIX C-4**. A comparison between the effectiveness of the operation of single and multiple groups of vehicles will be performed. As shown in **Table 5.2**, the total travel cost by operating multiple vehicles seems not less than the total travel cost of the case using a single vehicle. Adding the number of vehicle will not necessarily reduce the total travel cost due to the fact that routes must be operated in a particular sequence in disaster debris collection problem with blocked accesses; therefore the groups of vehicles still have limitation in their operation and must wait until one completes a particular part of operation. However, when minimization of total time was considered in the objective function instead of travel cost, there was a saving in the total travel time (*tt*) if the operation is performed by operating four groups of vehicles.

5.3.3 The Best Location of Disposal Sites

In this section, location factor of disposal sites or intermediate depots is the main issue that should be taken into account in performing cost optimization. Therefore, the optimization process determines optimum number of intermediate depot established the best location and minimum capacity of each. The model formulation of the disaster debris collection problem is applied on both Tokyo Eastern Area (Location A) and Tokyo Western Area (Location B) as also were tested in section **5.3.1**. The data which is used in this test, related to travel cost, travel time, demands, etc, as well as the assumptions can refer to the previous state in section **5.3.2**.

In location A, as shown in **Figure 5.13**, there are three candidate locations of depot as well as intermediate depot (node A, B and C). At this stage, the location of the depot and intermediate depot has not yet been decided, however only the candidates exist. The determination of these candidate locations considering that there are huge open spaces (*to be named*) close to the locations which could serve as vehicle parking area and disposal site. The road network in location A is assumed as a simple network with respect to relatively small number of roads exists. Therefore, only single intermediate depot as well as depot at the same location will be established (among node A, B or C); and then G_h could be ignored. After decided, node no.1 serves as depot, where vehicle starts and ends their tour; and the other nodes are debris collection points or the required nodes. Besides serving as depot, node no.1 is duplicated into the chosen node (among node A, B or C) which serves as intermediate depot. There exist distances between nodes called as *tc* which is calculated by the equation (1b). It is assumed that there are 20 standard dump truck vehicles involved in this disaster debris collection operation with an individual capacity of 10 ton each. Furthermore, they will be operated as one unit and thus will be treated as a single group of vehicles with unified capacity of 200 ton

Some fixed costs can be determined before running the optimization process i.e., total fixed vehicle cost (F_k) as well as total fixed travel cost (tc') which was calculated as 641.34 distance units. Subsequently, the total travel cost (tc) was calculated by applying the model formulation with the reduced demands; using tabu search, the best total travel cost (tc) obtained was 46.19 distance units with route as shown in **Figure 5.14** and **APPENDIX D-1**. Such optimum solution was obtained if the depot as well as the intermediate depot established at node A.

Furthermore, the same test is also applied in location B. In there, as shown in **Figure 5.15**, there are three candidate locations of depot as well as intermediate depot (node A, B and C). Because of the complexity of road network structure in location B with respect to more number of roads exists, other strategies are evaluated.

In case 1, only single intermediate depot as well as depot at the same location will be established (among node A, B or C); and then $G_h$could be ignored. After decided, node no.1

serves as depot, and it is duplicated into the chosen node (among node A, B or C) which serves as intermediate depot. There exist distances between nodes called as tc which is calculated by the equation (1b). In this case also, it is assumed that there are 20 standard dump truck vehicles involved in this operation with an individual capacity of 10 ton each working as a single group of vehicles with unified capacity of 200 ton. The total fixed travel cost (tc') was calculated as 6.95 distance units before running the optimization process. Subsequently, total travel cost (tc) is calculated by applying the model formulation; using tabu search, the best total travel cost (tc) obtained was 74.51 distance units with route as shown in **Figure 5.16** and **APPENDIX E-1**. Such optimum solution was obtained if the depot as well as the intermediate depot established at node A.

In case 2, multiple intermediate depots will be established. The depot has been decided to be established at node A, as well as the first intermediate depot at the same location because of the efficiency reason according to the result from previous case. However there are still two candidates of intermediate depot locations at node B and C. The number of subsequent intermediate depot which should be established, the best location and the minimum capacity each in order to minimize cost of the disaster debris collection operation are objectives function of this case. After completing the calculation process, the cost obtained of each possible combinations of intermediate depot establishment is shown in **Figure 5.17**. As seen that the best decision to establish intermediate depot is using scenario ABC i.e., at node A ($qi \geq 6606.08$ ton), B ($qi \geq 766.74$ ton) and C ($qi \geq 2289.94$ ton) at once, in order to obtain the cost optimum solution as 59.46 (tc'=55.48 and tc=3.98) and with route as shown in **APPENDIX E-2**. However in such condition G_h is not considered yet or assumed G_h to be 0. In the meantime, **Figure 5.18** shows condition G_h is considered due to there will be costs involved in setting up and closing a disposal site. Therefore the cost optimum solution is not only determined by the travel cost, but also the cost to establish the disposal site, such as cost for leasing public or private land, clearing area, building infrastructure, etc.

After the amount of G_h agreed upon, every additional number of intermediate depot should add G_h into the total cost. In this case, the scenario ABC still can be accepted if the total cost after added by G_h is still a minimum; or otherwise the scenario can be changed respect to the minimum cost.

In case 3, the problem is modified by considering of multiple groups of vehicles operation. It is assumed that there are four groups of vehicles with capacity of 50 ton each and all may have varying routes. As mentioned earlier, that multiple vehicles operation has

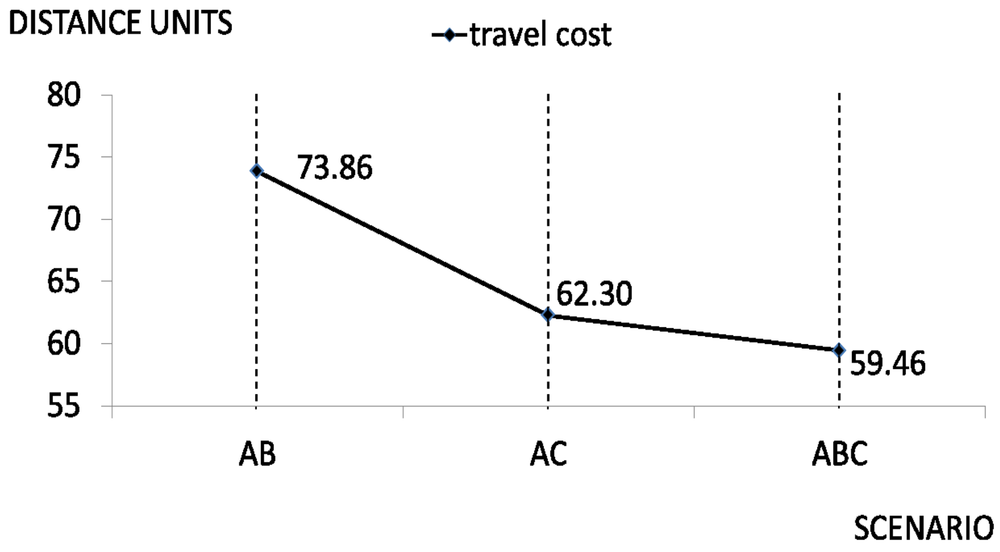


Figure 5.17 The scenario options without G_h

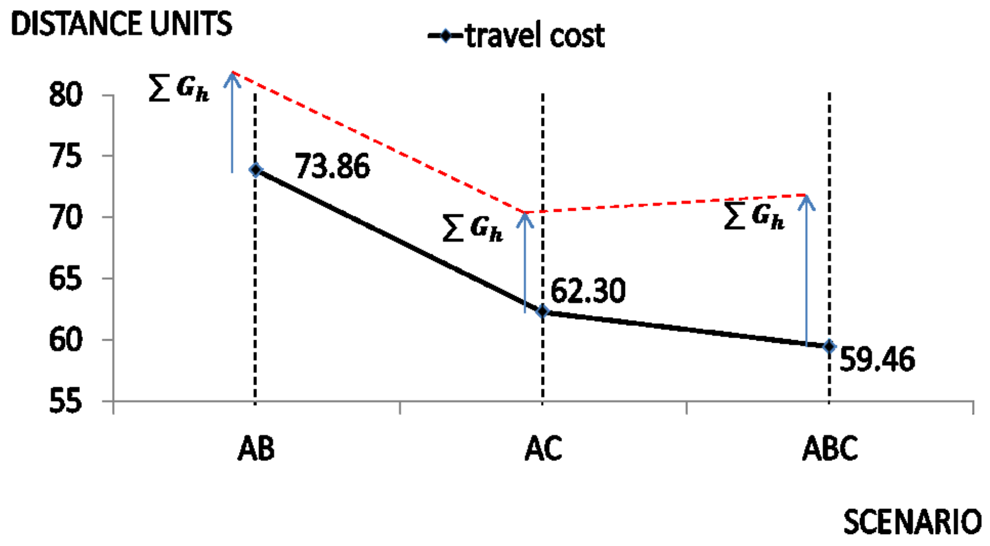


Figure 5.18 The scenario options with G_h

objective function to find the best required time (*tt*). In order to deal with this kind of problem, the L-CVRP was optimized by considering the time of operation instead of travel distance. After completing the calculation process, the total fixed required time (*tt'*) is 24.91 time units and the best total required time (*tt*) is 33.27 time units with route for each vehicle group as shown in **APPENDIX E-3**. Such optimum solution was obtained if the depot established at node A and the intermediate depot established at node A (qi≥6163.24 ton), B (qi≥483.06 ton) and C (qi≥3016.46 ton) at once.

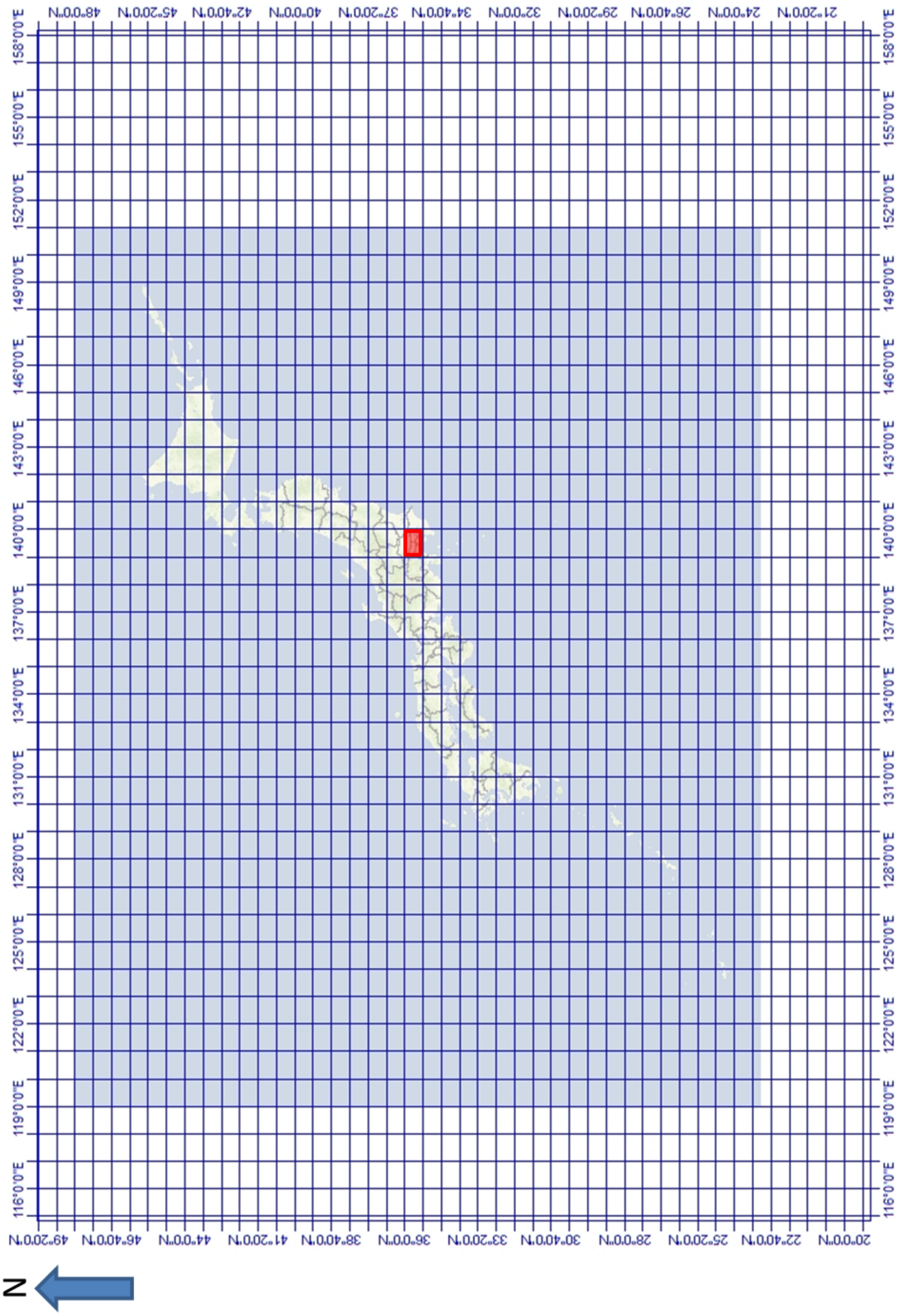


Figure 5.1 Tokyo Metropolitan Area in Japan Area

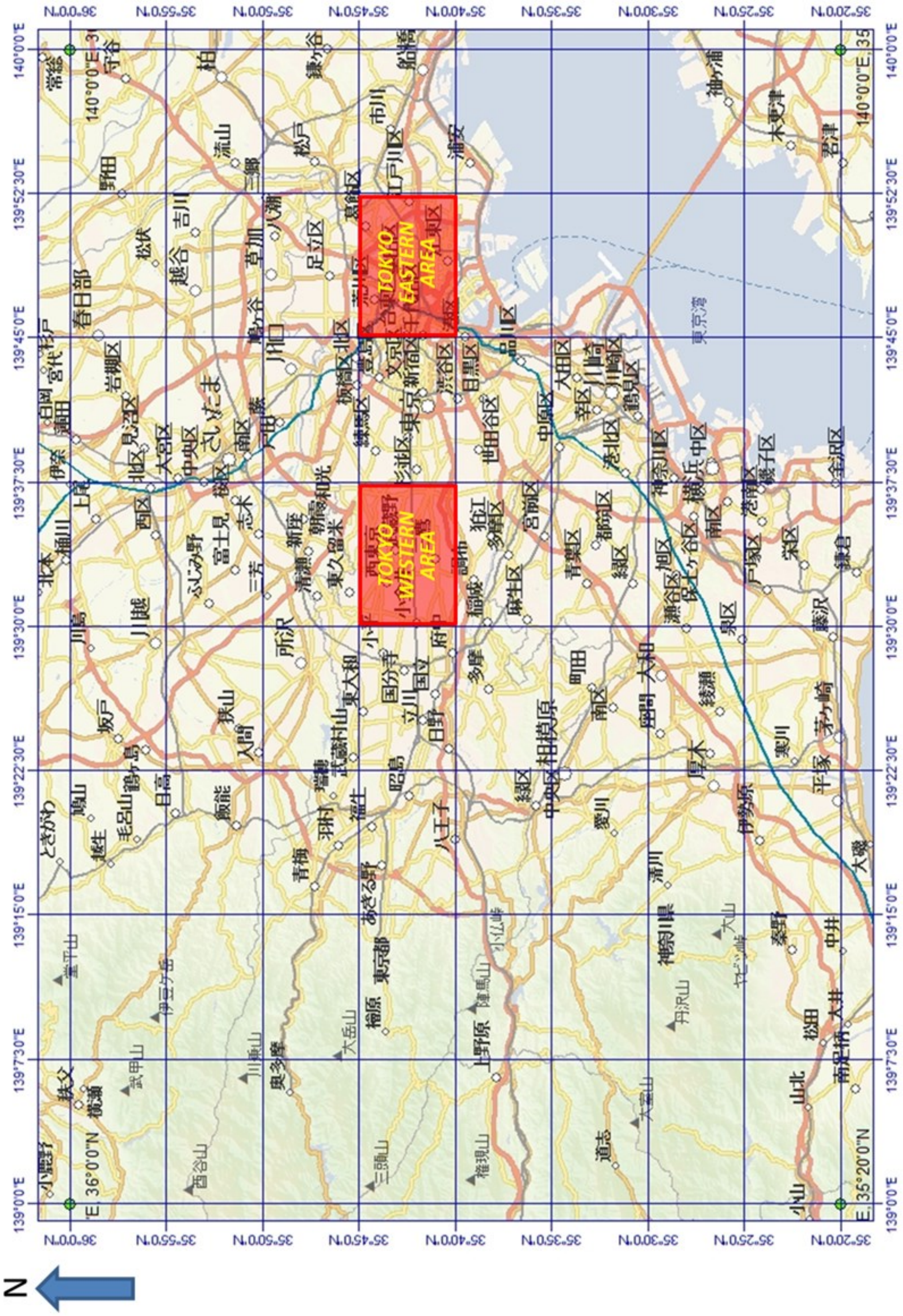


Figure 5.2 Tokyo Metropolitan Area

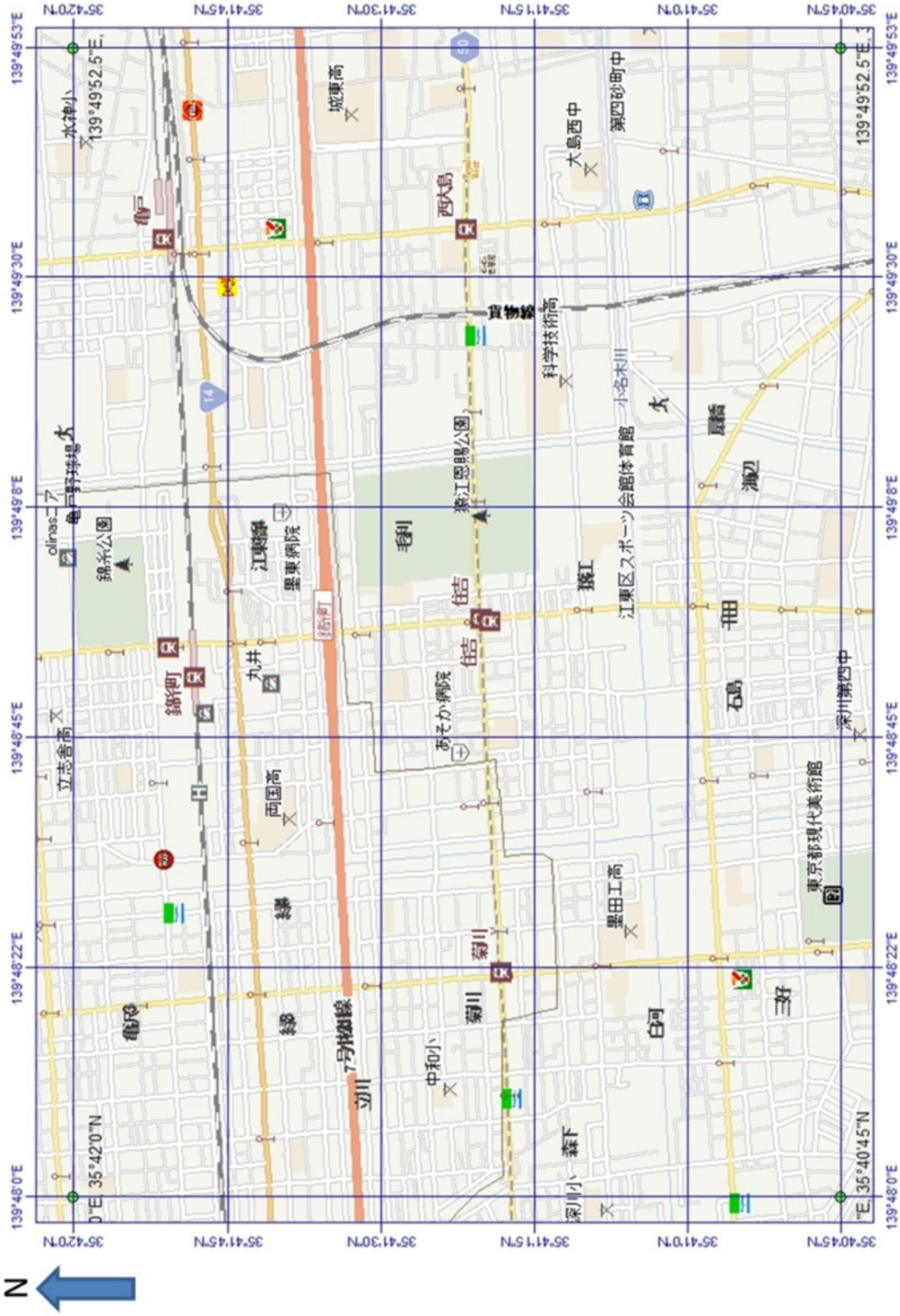


Figure 5.3 Tokyo Eastern Area (location A)

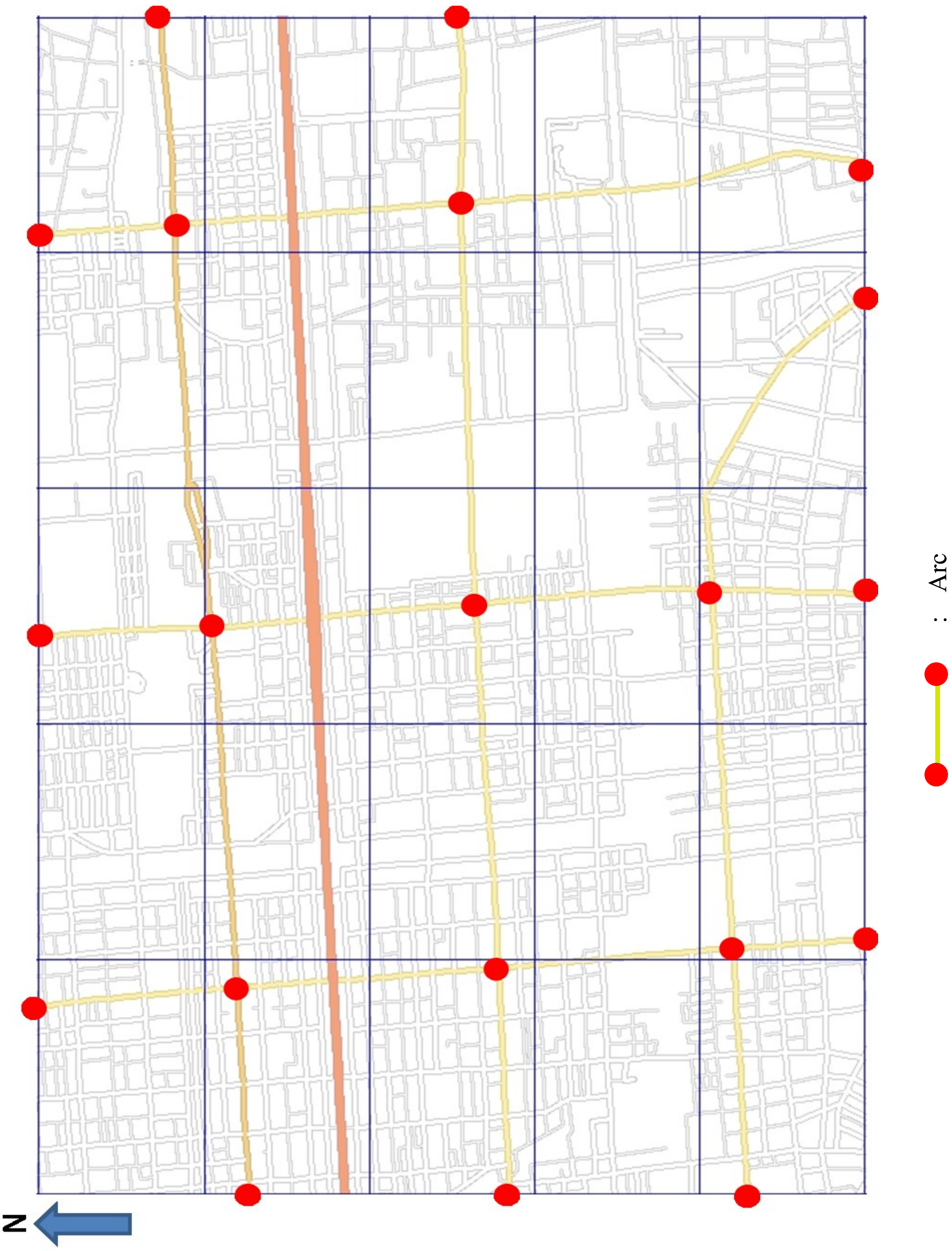


Figure 5.4 CARP in location A

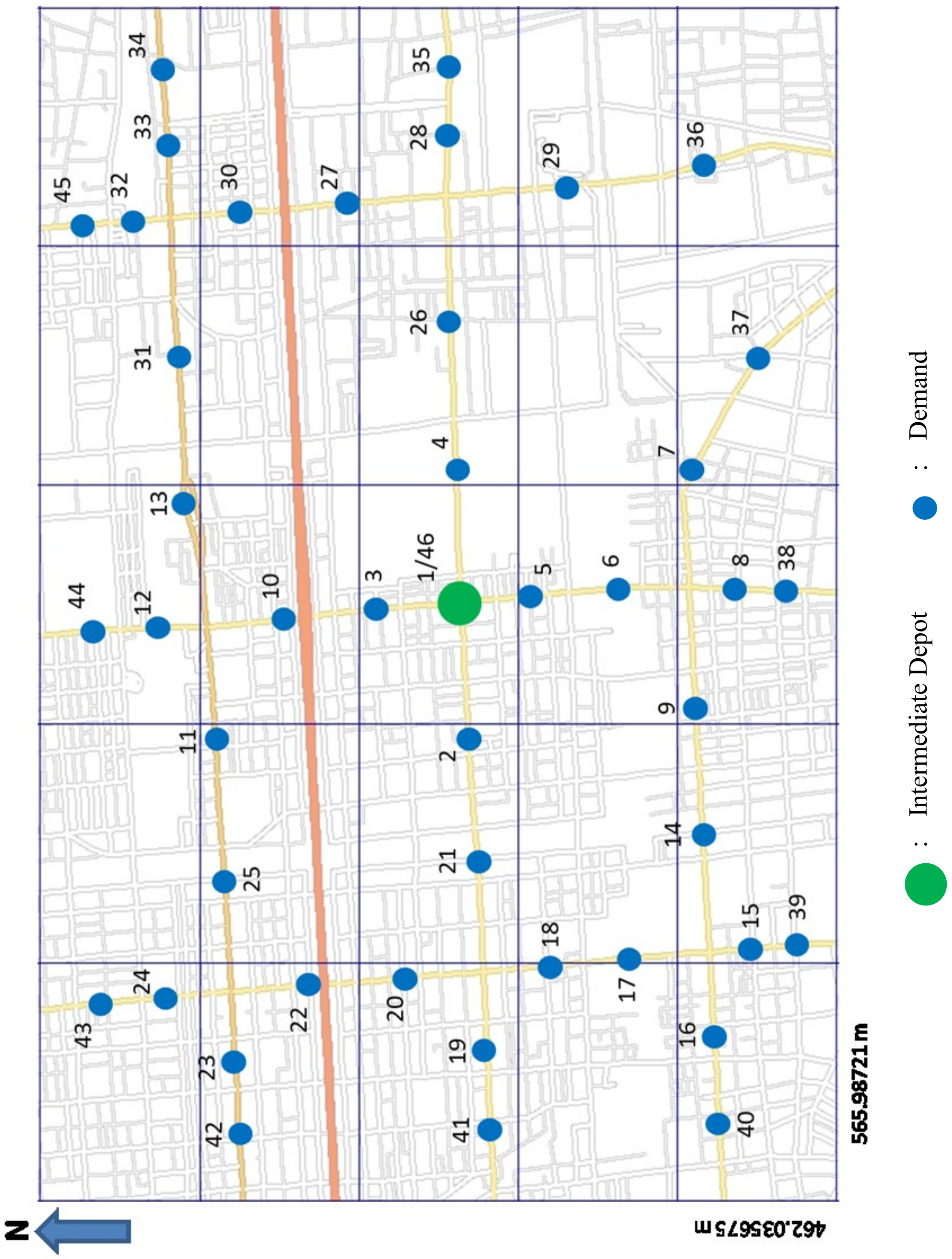


Figure 5.5 Application of CVRP in location A

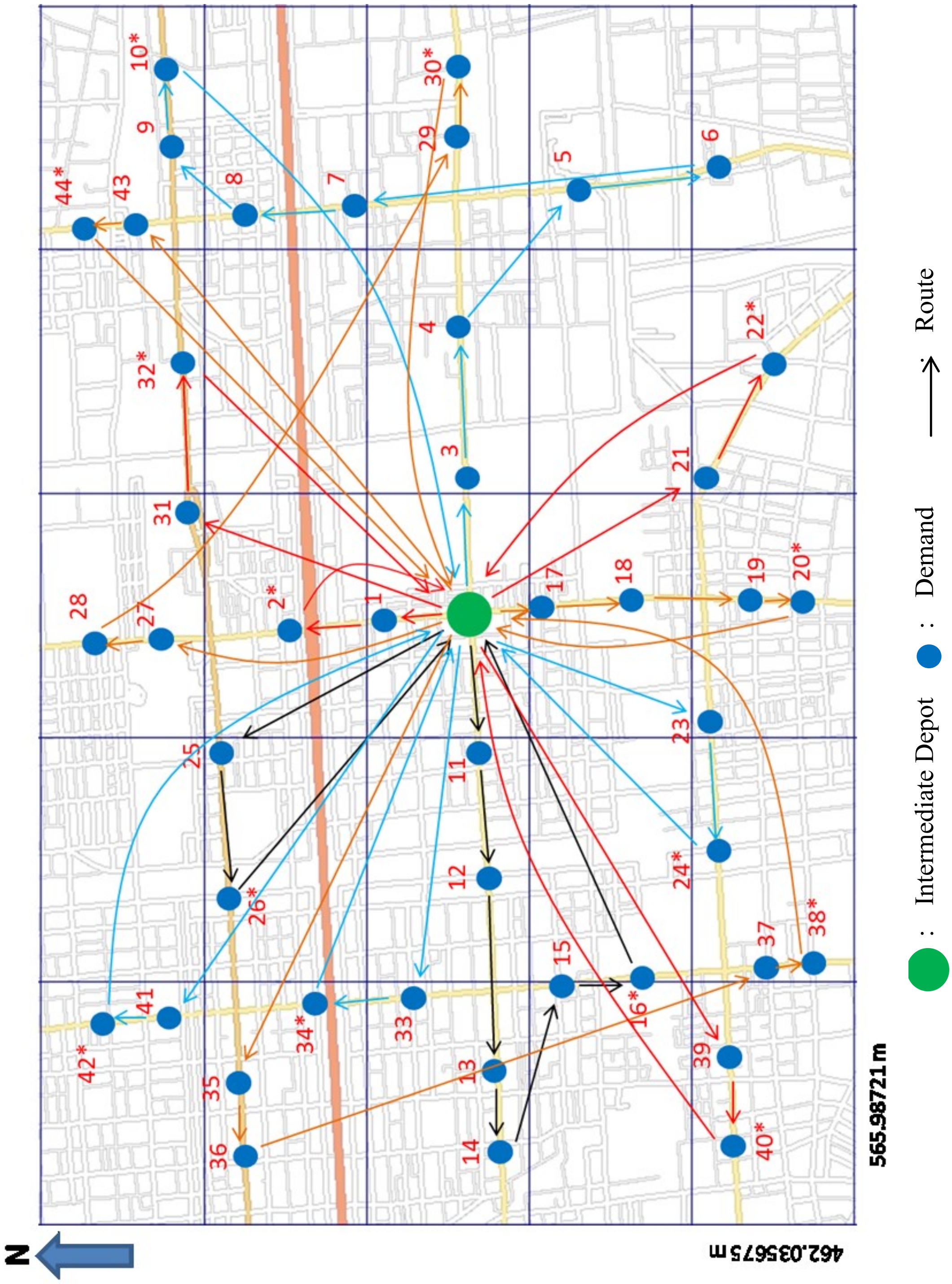


Figure 5.6 Route visualization of the solution in location A

Figure 5.7 Tokyo Western Area (location B)

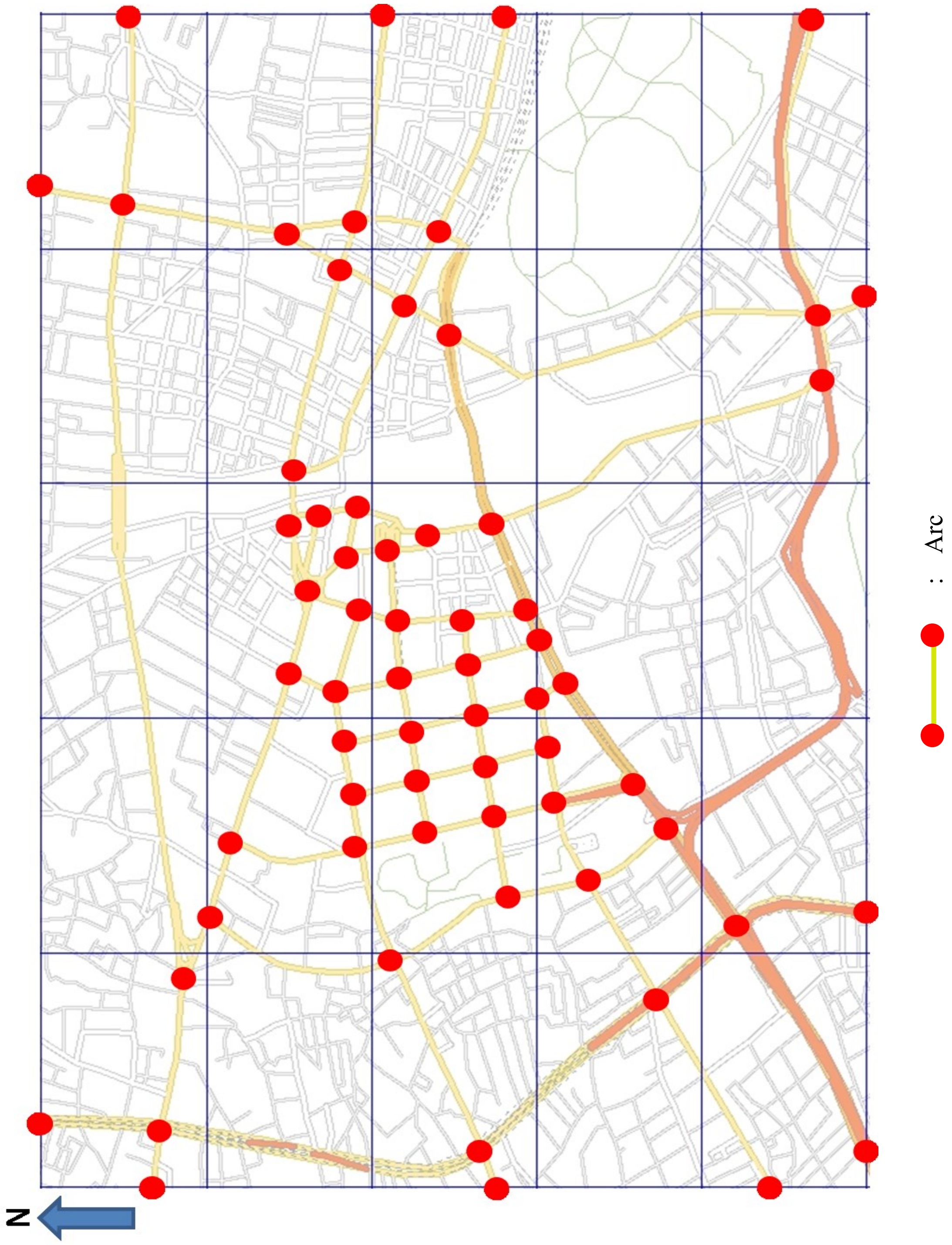


Figure 5.8 CARP in location B

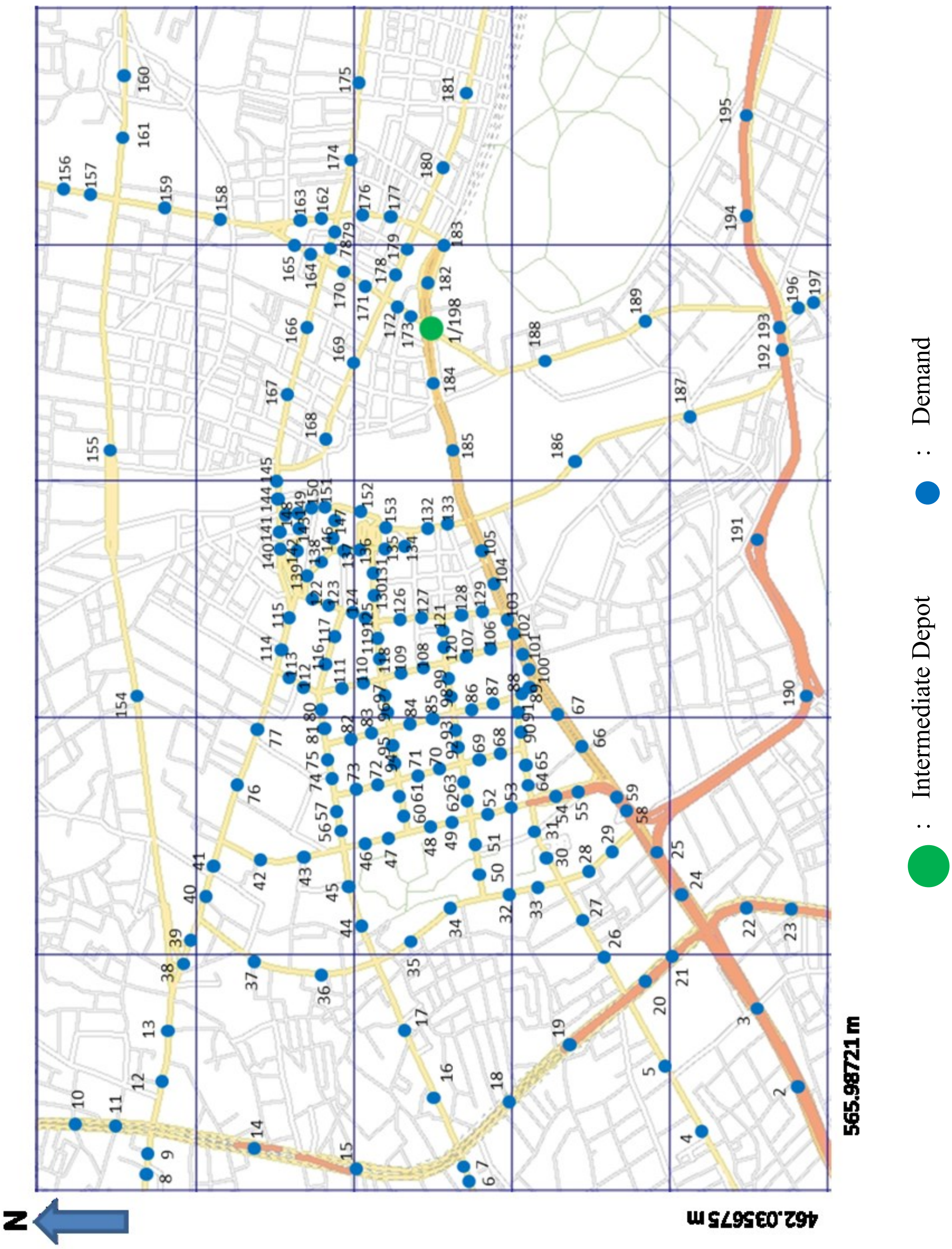


Figure 5.9 CVRP (single intermediate depot) in location B

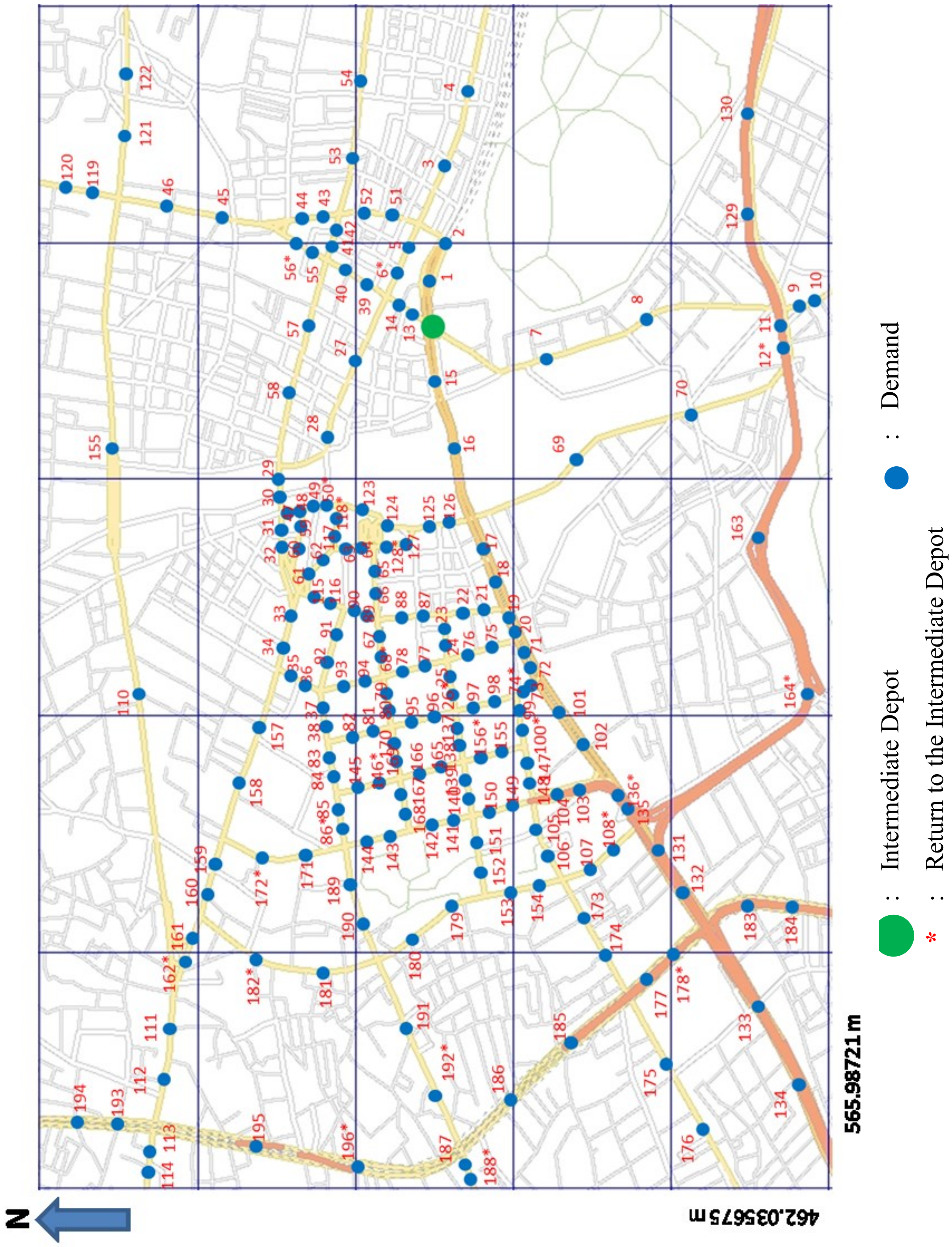


Figure 5.10 Route visualization of the solution in location B (case 1)

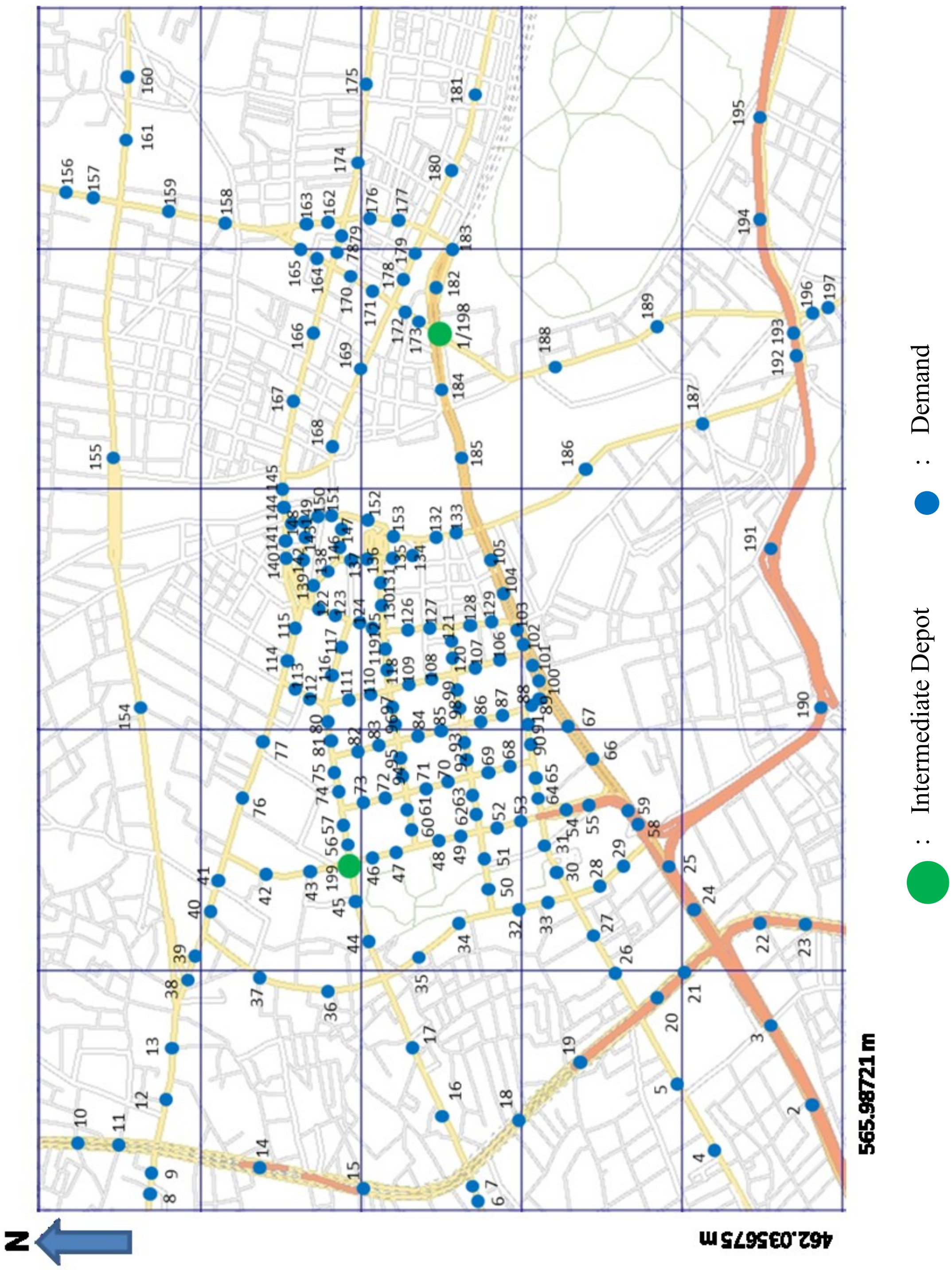


Figure 5.11 CVRP (2 intermediate depots) in location B

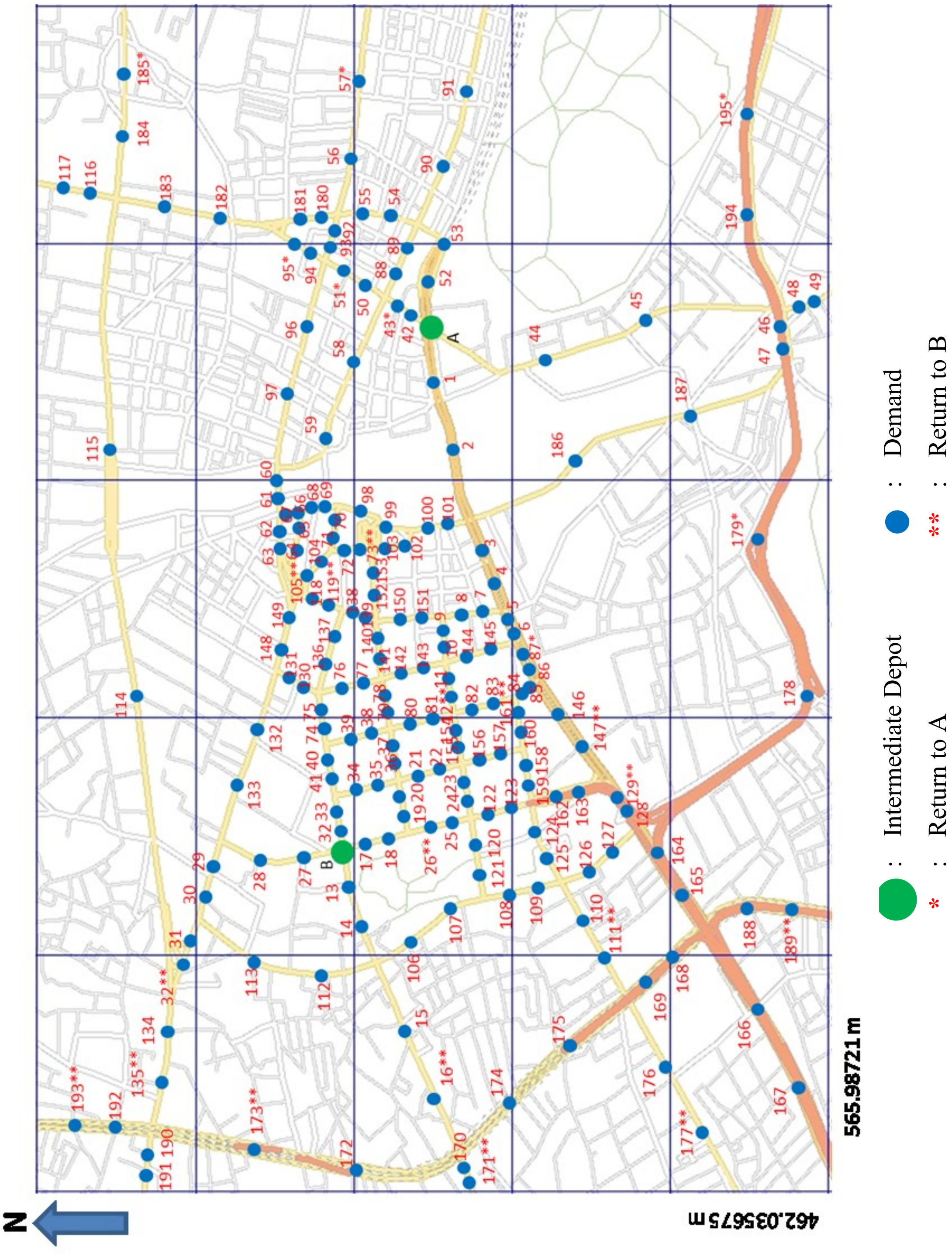


Figure 5.12 Route visualization of the solution in location B (case 2)

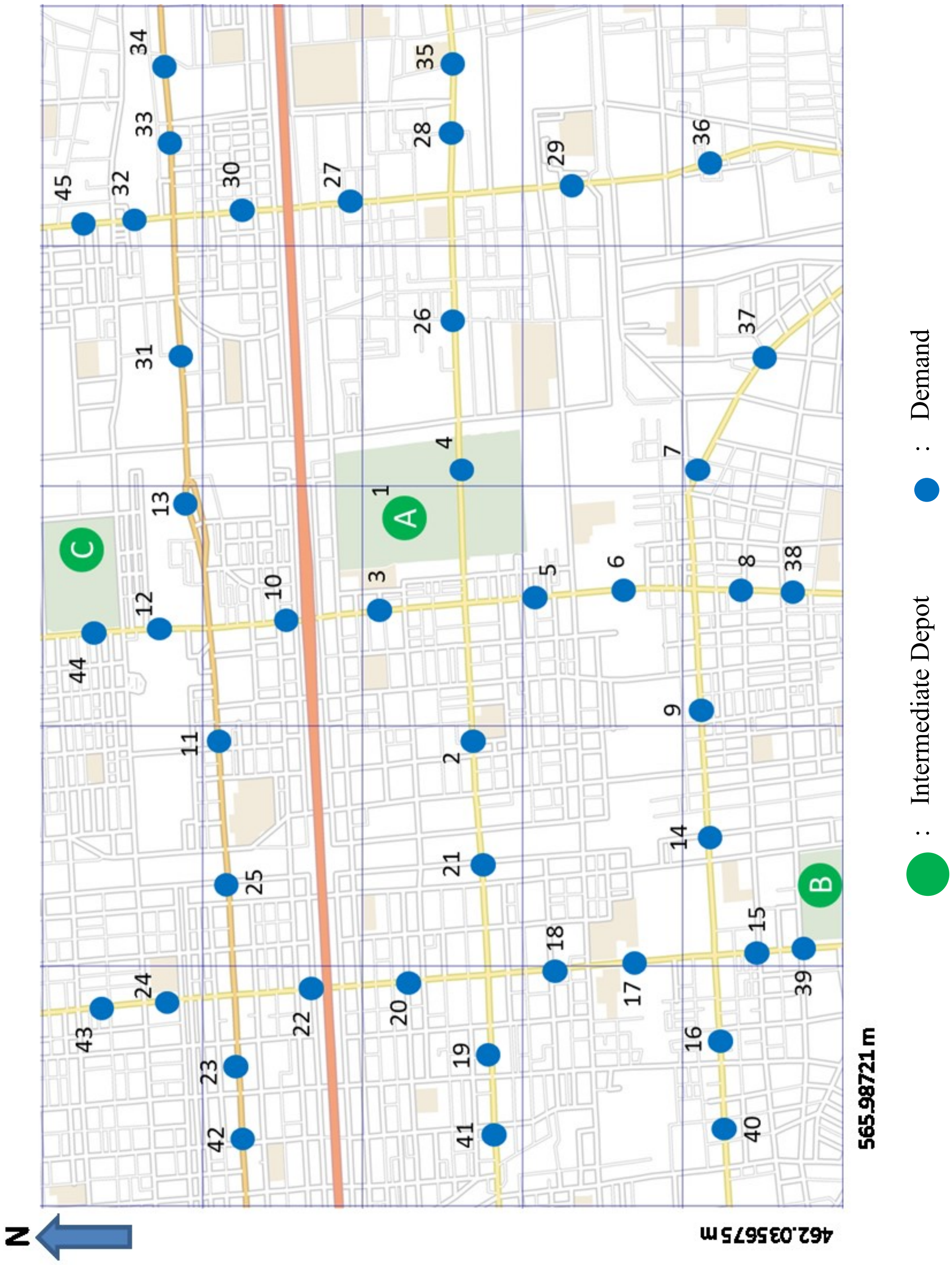


Figure 5.13 Application of L-CVRP in location A

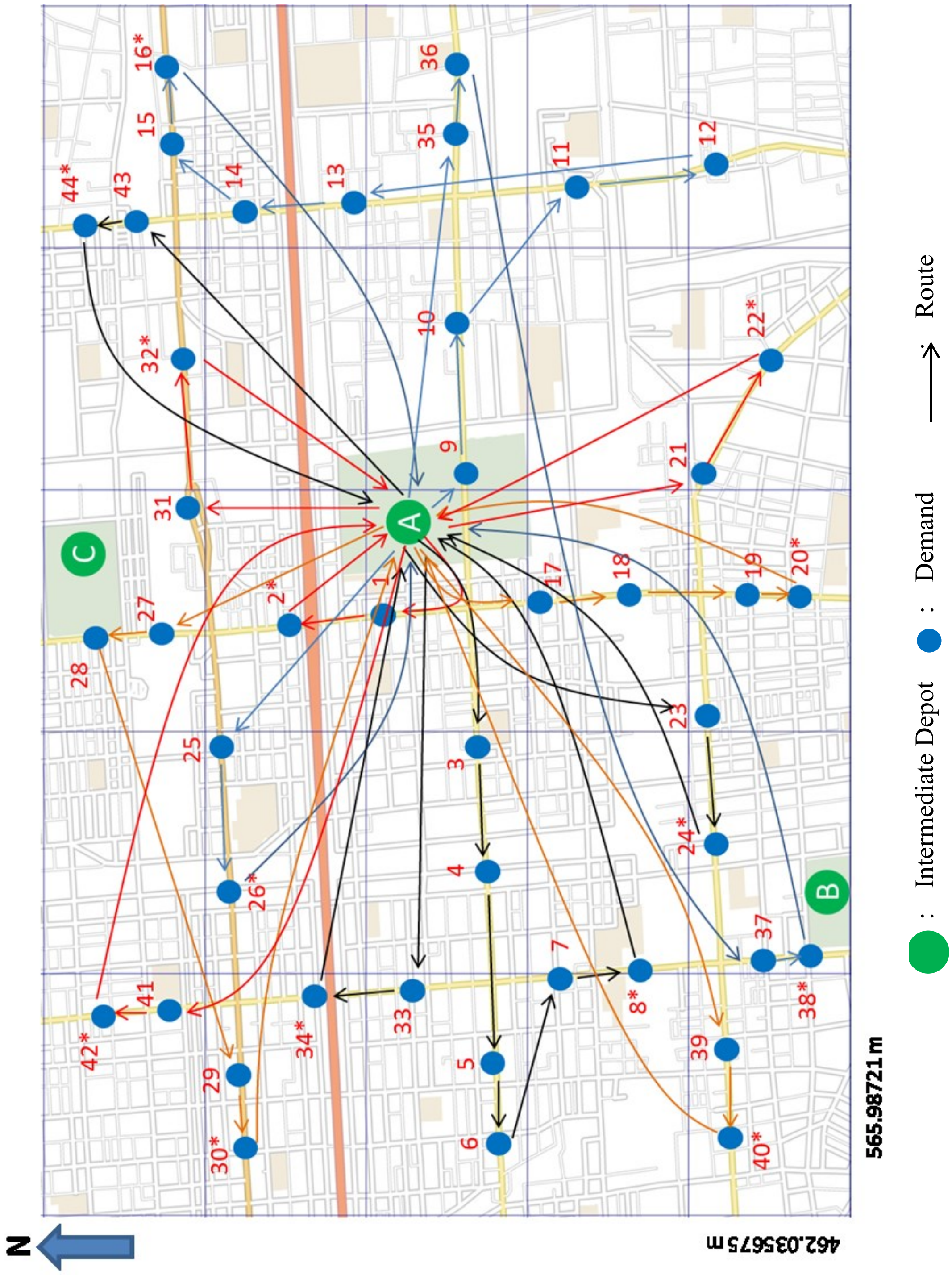


Figure 5.14 Route visualization of the L-CVRP solution in location A

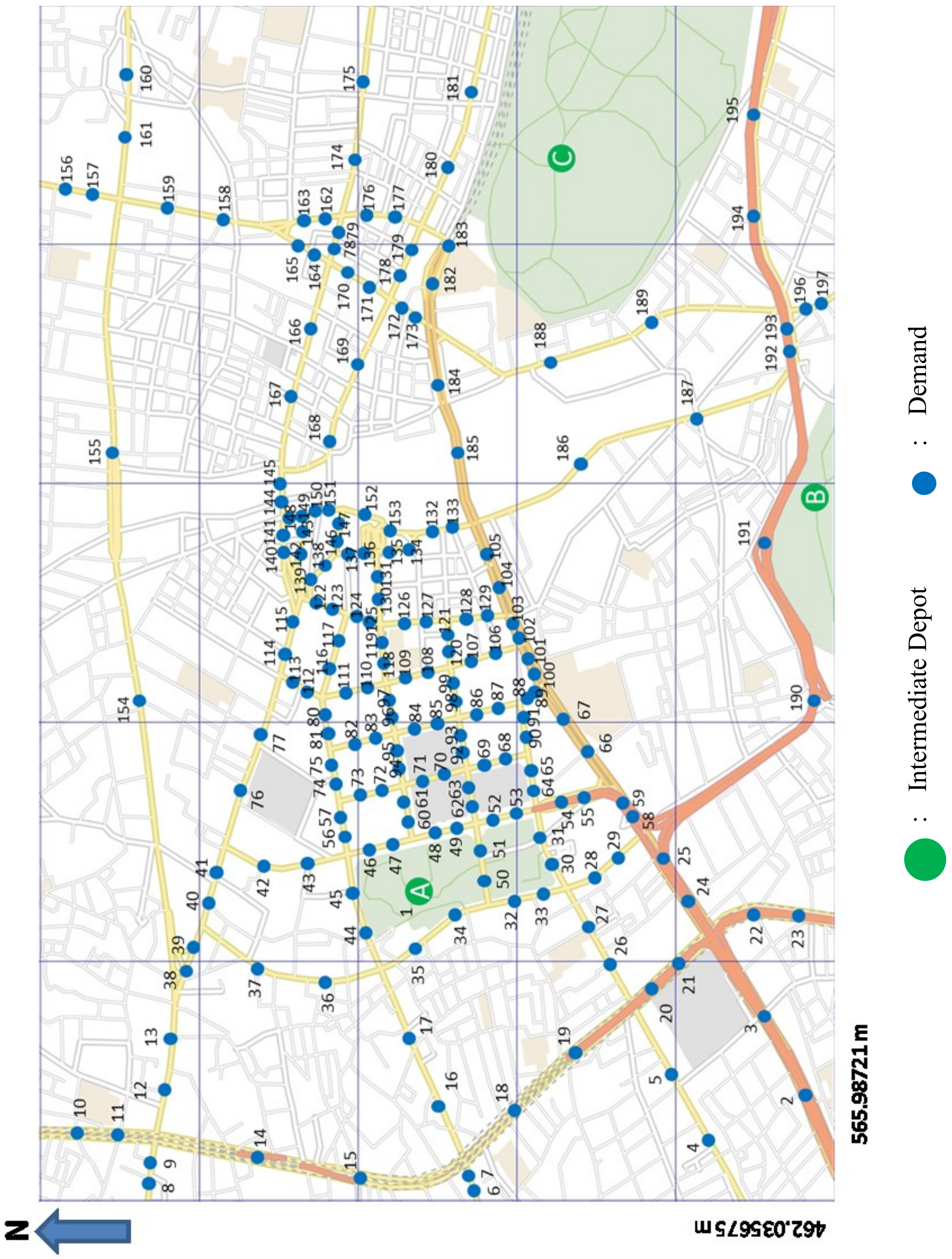


Figure 5.15 CVRP (single intermediate depot) in Location B

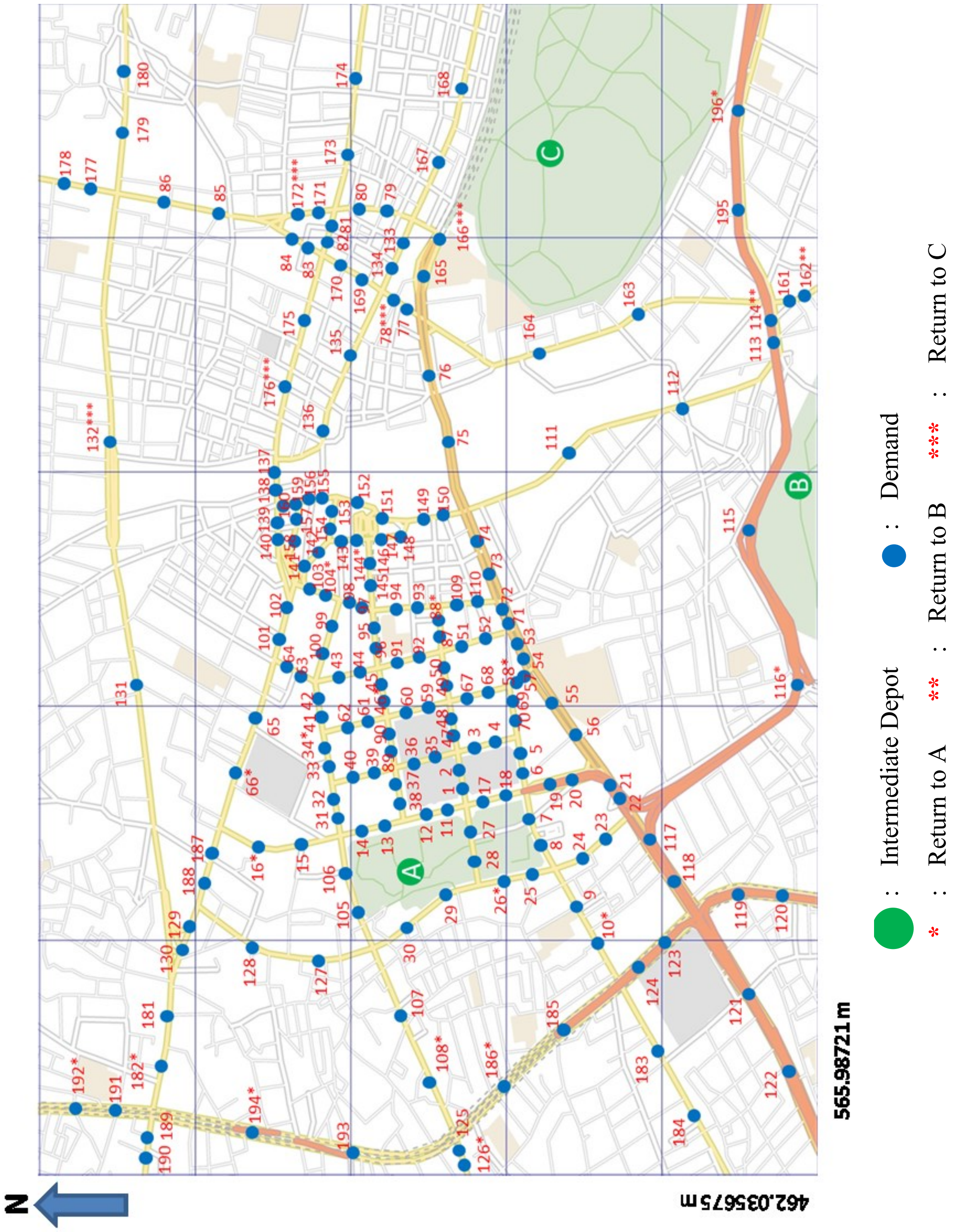


Figure 5.16 Route visualization of the L-CVRP solution in location B

5.4 Summary

An estimation procedure was established by Hirayama et al. (2010) to assess the amount of debris resulting from earthquake and flood disasters in Tokyo Metropolitan Area. It was shown that the procedure of disaster debris estimation in disaster management and operation systems could be established for not only emergency response in the aftermath, it can also be used in pre-disaster planning. In that case study, the amount of debris from earthquake and catastrophic flood disasters in Tokyo Metropolitan Area was estimated according to the hazard maps.

The data of disaster debris used in this study is estimation data as result from the study of “Establishment of Disaster Debris Management Based on Quantitative Estimation Using Natural Hazard Maps” by Hirayama et al. (2010). The result of estimation data of disaster debris amount of Tokyo Metropolitan Area is then used as a realistic case of our study.

Based on the assessment of debris resulting from earthquake and flood disasters in Tokyo Metropolitan Area, the amount of debris information was spread over 5 by 5 grid areas or 25 grid areas of 261,506 square meters each. Since the data result is not detailed, therefore the amount of debris which is spread on every road in each grid area needs to be calculated. In this paper, such calculation was performed by dividing the road area by the grid areas, and then multiplied by the sum of debris in corresponding grid area. In order to get data of road area, the road lengths are measured from existing Tokyo map; meanwhile the road widths are assumed as an average 3.25 m/lane and a total of 4 lanes were assumed for each road.

The model formulation of the disaster debris collection problem will be applied to solve the realistic case study which was assessed by Hirayama et al. (2010). Considering the large size of entire Tokyo Metropolitan Area, the model formulation will be tested in two spot locations only, representing eastern and western part of Tokyo. Location factor of disposal sites or intermediate depots is the main issue that should be taken into account in performing cost optimization. Therefore, the optimization process determines optimum number of intermediate depot established the best location and minimum capacity of each. The model formulation of the disaster debris collection problem is applied on both Tokyo Eastern Area (Location A) and Tokyo Western Area (Location B).

In the real life situations, demands (i.e., the amount of debris to be removed) in some arcs could very possibly exceed the vehicle capacity, so was the case also in this case study of Tokyo Metropolitan Area. Hence, in anticipating such situation, instead of a single vehicle some specified number of vehicles may be operated considering that they will work together in a group with the same route. Even after assuming a reasonable size of a unit group of vehicles, still because of limited capacity, the group of vehicles may not necessarily be able to service a single arc completely without returning to intermediate depot to empty the load. This condition can give rise to additional costs, which is defined as the commuting cost. The amount of the commuting cost can be calculated before the transformation from arcs into nodes with two additional equations.

References

1) Hirayama, N., Shimaoka, T., Fujiwara, T., Okayama, T. and Kawata, T. (2010). Establishment of Disaster Debris Management Based on Quantitative Estimation Using Natural Hazard Maps. In: Waste Management and the Environment V. WIT Press.

Chapter 6

Conclusions and Future Research

6.1 Conclusions

Based on fact that year by year number of disaster events occurred in around the world significantly increased, the existence of disaster and emergency management is compulsory needed. FEMA (2007) reported that the concerning and legislation of disaster and emergency management was starting from the Congressional Act of 1803. Finally in March 2003, FEMA along with twenty two other agencies, programs and office became the Department of Homeland Security. Currently, disaster and emergency management is broadly realized as a concept which should be developed continuously in anticipating disaster events around the world.

The basic task of a logistics system is to deliver the appropriate supplies, in good condition, in the quantities required, and at the places and time they are needed, therefore logistics plays a critical role in disaster and emergency management. A branch of logistics which specializes in organizing the delivery and warehousing of supplies during natural disasters or complex emergencies to the affected area and people is recognized as humanitarian logistics. The important role of logistics during the disaster response phase is on the humanitarian relief operation. However, another important role of logistics is on the debris removal (collection) operation which can be considered as an operation to remove the debris which blocks road in order to rebuild access connectivity. The access connectivity is highly impacts on humanitarian relief distribution process. In case of debris blocked road and disrupt the access connectivity, the humanitarian relief distribution would experience deceleration.

The activities of debris removal operation in disaster waste management are including the sorting, collection, handling, transportation and treatment (recovery as well as disposal) of disaster waste. Our disaster debris collection operation research is a part of debris removal operation since as mentioned that both collection and transportation to the disposal site activity are including in the debris removal operation. Therefore, from frame description of disaster waste management phases and the property authority of debris removal operation above, we narrow the scope of our research only in the early recovery phase and public property debris removal category. It is considering that the objective research is to emphasize on the activity of debris collection that existing in the early recovery phase; and to open blockage and rebuild of road network connectivity by collecting debris in the public area.

In every technical operation generally and every disaster debris collection operation particularly, cost usually becomes big issue. Actually, increasing of the operations cost is not an issue that cannot be avoided because most of such cases are caused by inefficiency factor. Inefficiency in the disaster debris collection operation may be caused of many aspects; however one of them which also become the research focus is the aspect in association with logistics and transportations, particularly routing and location problems. Therefore, a route optimization should be involved in vehicle routing and disposal sites location plan in order to calculate the optimum cost. Route optimization is a useful tool to optimize logistics operations due to result in the least possible number of vehicles required to serve all the demands, traveling as minimum a distance as possible and decreasing the idling time of the vehicles. We refine searching on the routing problem issues limited only into Capacitated Arc Routing Problem (CARP) variant. CARP is an underlying of the problem exists in our disaster debris collection operation research.

We research a variant of the undirected CARP; therein roads are treated as a set of arcs. A set of required arcs consists of arcs that are covered by debris, thus they have demands to service. The objective function of the CARP is to service all required arcs in the graph at least cost with feasible vehicle routes. Besides routing issue, the determining of number, location and capacity of the disposal site, termed as intermediate depot, is considered very important due to affect the vehicle routes in the operation.

The disaster debris collection operation is a new CARP problem and not much research has been done in this topic. The uniqueness of this kind of CARP problem is due to the limited access from one section to the other, as a result of the blocked access by debris. Therefore a modification in the classical CARP is required to solve this kind of problem. It is performed by adding a new dynamic constraint, which is developed in this research as access possibility constraint. This constraint sets whether a vehicle can possibly move from one node to another in a particular network, or not. Depending on the field conditions, p_{ij}^{k} constraint can be flexibly modified. In this case research, the p_{ij}^{k} was set to a maximum closed where only adjacent arcs can be connected with each other, while for distant arcs it was assumed that there may be no way to be connect them before removing the blocked access first. The access possibility matrix dynamically changes with servicing of each required arc or node of the problem, depicting the fact that the serviced arc may open up access to the other arcs.

In order to assess the accuracy of the tabu search algorithm more conclusively, we performed a computational experiment on a set of benchmark problems and compared the result with best known solutions for the 25, 50 and 100 customer instances of Solomon's Vehicle Routing Problem with Time Windows (VRPTW) benchmark problems (Solomon, 1987). Most of the Solomon's VRPTW problems consisting of 25 customers were solved by the tabu search within reasonable time and with relatively small optimality gap. Some Solomon's VRPTW problems consisting of 50 and 100 customers were also solved by the tabu search. In light of this computational experiment it can be concluded that the designed tabu search heuristics has sufficient efficiency. This may also be noted that the tabu search meta-heuristics is designed for non-time windows. Therefore even a better performance is expected for the debris collection operation.

In order to make rational decisions about the reality of the model formulated, firstly a hypothetical test instance was performed. It has done by creating small problem instances with artificial network and performed into four scenarios i.e., single intermediate depot and single vehicle; multi intermediate depots and single vehicle; multi intermediate depots and multi vehicles; and the best location of intermediate depot. Finally, a practical case study of Tokyo Metropolitan Area was conducted to estimate feasibility of the formulation and its solution algorithm. Dividing the area in location A (eastern part) and location B (western part) according to the complexity of the associated road network in terms of number of arcs, the case study was successfully solved. The optimized routes were improved significantly over the initial feasible solutions. It was shown that the problem formulation and the tabu search meta-heuristics algorithm can solve large scale, realistic and complicated instances with the reasonable computation time.

Routing is one of the most important aspects of finding cost optimum solution in the disaster debris collection operation. In addition, it has been demonstrated in this research that location of the disposal sites also greatly affected the cost. The calculation in finding the best solution has been done for all candidate locations of disposal site related to the number, the location as well as the minimum capacity, as main parts of this research. Hence the disaster debris collection operation problem solving by taking into account combination of routing and location aspects would obtain a better solution than solving it viewed from single aspect only.

In the real life situations, demands (i.e., the amount of debris to be removed) in some arcs could very possibly exceed the vehicle capacity, so was the case also in this case study of Tokyo Metropolitan Area. Hence, in anticipating such situation, instead of a single vehicle some specified number of vehicles may be operated considering that they will work together in a group with the same route. Even after assuming a reasonable size of a unit group of vehicles, still because of limited capacity, the group of vehicles may not necessarily be able to service a single arc completely without returning to intermediate depot to empty the load. This condition can give rise to additional costs, which is defined as the commuting cost. The amount of the commuting cost can be calculated before the transformation from arcs into nodes with two additional equations in the model formulation.

Based on both the hypothetical test instance and the realistic case study of Tokyo Metropolitan Area tested in this research, it can be concluded that: (i) establishing multiple intermediate depots can effectively decrease total travel cost (*tc*), however such decrease shall be carefully analyzed in case one need to include the establishment cost of the intermediate depot; (ii) operating multiple vehicles may not effectively decrease total travel cost (*tc*), considering that working in a network with blocked access imposes the conditions that routes must be operated in a particular sequence; (iii) operating multiple vehicles can effectively decrease total required time (*tt*) which is appropriate in operations with time restrictions either at disposal site or at depot; and (iv) locating intermediate depots with good decision related to the number, the location, as well as the minimum capacity, greatly affect the total travel cost (*tc*) and total required time (*tt*).

The academic contribution is developing the model algorithm with new idea of intermediate depot and additional constraint p_{ij}^{k}, as well as the practical contribution is proposing a post disaster planning technique about debris management that can be applied in preparedness phase.

6.2 Topics for Future Research

Considering that has not much research conducted in the topic of disaster debris collection operation, thus we propose some topics that may be future researches. In addition, such proposed researches are expected to complement and enhance the results of our research. We divide the recommended topics for future research into three categories as follows:

- Developing understanding on the issue of disaster debris collection operation itself. The idea is by conducting research about synchronized arc routing for disaster debris collection operations, as well as about applying the model of disaster debris collection operation on best practices of disaster debris removal problems, such as the Haiti Earthquake in 2010, the Great East Japan Earthquake in 2011, etc. By comparing the result between solution obtained from academic research and solutions which has been done in the real case, the gaps and incompatibilities may be reviewed and studied.

- Developing the assumptions taken in our research i.e., (i) the shortest path from node i to node j in graph is the only path that exists for every node pair. Accordingly, the connection between i and j depends on whether $d(i,j)$ is blocked or not, however if j is depot or intermediate depot, the vehicle always can move from i to j through the shortest path. In the proposed topic, new assumption would be taken i.e., the shortest path from node i to node j in graph could more than one, therefore if the 1st shortest path blocked by debris vehicle still can move through the 2nd, 3rd, … shortest path; (ii) the p_{ij}^k was set to a maximum closed where only adjacent arcs can be connected with each other, while for distant arcs it was assumed that there may be no way to be connect them before removing the blocked access first. In the proposed topic, new assumption would be taken i.e., the accessibility regarding the p_{ij}^k constraint could be relaxed. Such modification applied on p_{ij}^k constraint; would suggest that as long as there exist other paths from node i to node j, vehicle k still can possibly move from node i to node j even though without traversing the blocked shortest path; (iii) the road has the same priority to service. New assumption would be taken that each road has difference level of urgency. Some roads may be in advance priority due to connecting importance points or locations; whereby differently from our case problem that assuming all roads have the same priority scale. Another topic proposed is by adding input of debris priority, which means that debris in each road has difference level of urgency. The urgency level of debris respect to type, location, etc.; for example, hazardous material debris definitely high level of priority to be removed first; and (iv) another topic proposed is by considering the real cost to establish intermediate depot, which serves as the disposal site.
- Next topic proposed is about multi objective optimization on the humanitarian logistics operations. It would be an area of multiple criteria decision making, which is concerned with mathematical optimization problems involving objective function for evacuation, relief distribution and disaster debris collection operation to be optimized simultaneously. This topic is important considering that among such operations in the context of humanitarian logistics, there is a very close association and mutual support.

Appendix A

APPENDIX A-1

Debris Resulting from Earthquake and Flood Disasters in Tokyo Metropolitan Area

mesh code	value (ton)
523834701	0.000277547
523834703	0.001444379
523834801	0.001428547
523844401	8.50E-06
523844403	0.000379503
523844501	0.00156616
523844503	0.000379503
523844601	3.39854E-05
523844603	2.83E-06
523854201	3.39854E-05
523854203	2.5489E-05
523854403	0.00016964
523854501	3.57137E-05
523854503	1.78568E-05
523854803	2.73189E-05
523864201	0.000630067
523864203	0.001023858
523864303	8.616E-05
523864503	0.000131947
523864601	0.000105558
523864801	0.000554178
523874601	0.000105558
523874701	0.000211115
523874801	0.000105558
533814403	0.000157517
533814503	0.000818072
533814603	0.000236275
533814703	0.000369452
533814903	0.001338892

mesh code	value (ton)
533824001	0.000263894
533824003	7.91682E-05
533824101	0.001968958
533824203	0.000395841
533824603	0.006851975
533824701	0.026226524
533824703	0.020477166
533824801	0.120403666
533824803	0.494384748
533824901	0.038310257
533824903	0.038310257
533834001	0.125876559
533834003	0.29553627
533834101	0.426885723
533834103	0.40316985
533834201	0.01824298
533834303	0.000315033
533834401	0.047431747
533834403	0.001824298
533834601	0.016418682
533834803	0.007297192
533834901	0.078444812
533834903	0.322900739
533844001	0.00708825
533844003	0.000551308
533844101	0.003150333
533844103	0.0151216
533844201	0.040419178
533844203	0.025491641

mesh code	value (ton)
533844301	0.020162133
533844303	0.0018902
533844403	0.000229654
533844801	0.000708825
533854103	0.00047255
533854201	0.000551308
533864201	0.000393792
533864203	0.00047255
533864401	6.70E-06
533874803	1.8331E-05
533874901	3.14246E-05
533874903	3.6662E-05
543804001	0.000107748
543804601	7.86E-06
543804701	1.28E-07
543804703	1.47E-07
543804801	5.51E-07
543814001	3.67E-08
543814003	7.34E-08
543814101	3.67E-08
543814103	2.94E-07
543814701	2.61872E-05
543814703	0.000141411
543814801	3.68599E-05
543814803	5.61E-06
543814901	5.51E-08
543814903	3.67E-08
543824003	5.32E-07
543824101	4.08664E-05

mesh code	value (ton)
543824301	2.08339E-05
543824303	8.57393E-05
543824401	7.21E-06
543824403	3.52573E-05
543824501	4.56742E-05
543824503	1.36221E-05
543824601	7.07054E-05
543824603	0.00012308
543824701	0.000191166
543824703	0.00018331
543824801	4.02E-06
543824803	2.37E-07
543834001	4.2469E-05
543834003	9.85602E-05
543834101	6.8912E-05
543834103	8.4938E-05
543834201	9.46E-06
543834203	2.55547E-05
543834301	2.37E-06
543834303	1.15943E-05
543834401	3.218E-05
543834403	3.55E-06
543834501	2.60E-06
543834601	7.10E-07
543834603	1.18309E-05
543834701	3.92785E-05
543834703	1.82195E-05
543834801	1.01746E-05
543834803	2.79209E-05
543834901	1.51435E-05
543834903	9.70E-06
543844001	5.92E-06
543844003	7.34E-06
543844101	3.79E-06
543854603	7.14E-08
543854901	1.21E-06
543854903	1.36E-06
523834704	0.000807153
523834802	0.005490979
523834804	0.002366032
523834902	0.002368775
523834904	0.029135937
523844002	0.027435651

mesh code	value (ton)
523844502	0.000184087
523844504	0.000461635
523854002	0.000473206
523854104	0.000472963
523854202	7.92992E-05
523854302	3.57137E-05
523854304	0.000276781
523854402	0.000776773
523854404	0.000464278
523854502	0.000116069
523864004	2.73189E-05
523864102	3.57137E-05
523864204	7.87583E-05
523864402	7.91682E-05
523864504	0.000131947
523864602	7.91682E-05
523864604	0.00087085
523864702	0.000686125
523864704	0.000131947
523864802	7.91682E-05
533814404	0.000236275
533814602	0.001102617
533814604	0.000866342
533814702	2.63894E-05
533814704	0.000765293
533824604	0.0018902
533824702	0.018193175
533824704	0.017799383
533824802	0.078444812
533824804	0.00912149
533824902	0.012770086
533824904	0.096687792
533834002	0.001824298
533834004	0.166011115
533834102	0.054728939
533834104	0.052904641
533834202	0.001824298
533834204	0.156889625
533834302	0.018114416
533834304	0.006221908
533834402	0.446953001
533834404	0.175132604
533834504	0.005472894

mesh code	value (ton)
533834602	0.131349453
533834604	0.430534319
533834702	0.589248242
533834704	0.020067278
533834802	0.184254094
533834804	0.040134555
533834902	0.432358617
533834904	0.729719185
533844002	0.01653925
533844004	0.010159825
533844102	0.000866342
533844104	0.011498716
533844202	0.052131553
533844204	0.012860647
533844302	0.004567983
533844402	0.000459309
533844404	0.000459309
533854104	0.000236275
533864402	2.67998E-05
533864404	5.02E-06
533864502	0.000158336
533874504	2.62E-06
533874704	1.30936E-05
543804002	4.97297E-05
543804004	1.65766E-05
543804702	3.49E-07
543804802	1.84E-08
543814104	3.67E-08
543814202	1.10E-07
543814602	1.84E-08
543814604	5.51E-08
543814702	2.09497E-05
543814704	0.000188548
543814802	3.28534E-05
543814804	3.52573E-05
543814902	3.67E-08
543824102	1.28208E-05
543824302	0.000100163
543824304	1.28208E-05
543824504	8.01E-07
543824602	0.000233066
543824604	1.57123E-05
543824704	0.000269728

APPENDIX A-2

Standard Grid Square and Grid Square Code Used for the Statistics (Announcement No. 143 by the Administrative Management Agency on July, 12, 1973)

The Standard Grid Square and the Grid Square Code used for the statistics are as follows: (Refer to: Explanation Chart)

1. Standard Grid Square

The Standard Grid Square includes the following three kinds of Grid Squares:
the Basic Grid Square;
the Divided Grid Square that a Basic Grid Square has divided;
the Integrated Grid Square that some Basic Grid Squares have integrated.

(1) Basic Grid Square

The Basic Grid Squares are to be compiled according to the methods shown below:

A. Compile the Primary Area Partition by dividing the whole area of Japan into blocks measuring 1 degree of longitude by 2/3 degree of latitude.

B. Divide the Primary Area Partition into 64 (8 by 8) equal parts along longitude and latitude to compile the Secondary Area Partitions.

C. Divide the Secondary Area Partition into 100 (10 by 10) equal parts along longitude and latitude to compile the Third Area Partitions, which are equal to the Basic Grid Squares.

(2) Divided Grid Square

The Divided Grid Square includes the following three kinds of Grid Squares:
the Half Grid Square that the side length is one half of the Basic Grid Square;
the Quarter Grid Square that the side length is one quarter of the Basic Grid Square;
the Eighth Grid Square that the side length is one eighth of the Basic Grid Square.
The following table shows how to compile:

Category	How to compile
Half Grid Square	Divide a Basic Grid Squares into 4 equal parts: 2 by 2.
Quarter Grid Square	Divide a Basic Grid Squares into 16 equal parts: 4 by 4.
Eighth Grid Square	Divide a Basic Grid Squares into 64 equal parts: 8 by 8.

(3) Integrated Grid Square

The Integrated Grid Square includes the following three kinds of Grid Squares:
The Double Grid Square that the side length is double of the Basic Grid Square;
The Quintuple Grid Square that the side length is quintuple of the Basic Grid Square;
The Decuple Grid Square that the side length is decuple of the Basic Grid Square.
The following table shows how to compile:

Category	How to compile
Double Grid Square	Divide a Secondary Area Partition into 25 equal parts: 5 by 5
Quintuple Grid Square	Divide a Secondary Area Partition into 4 equal parts: 2 by 2
Decuple Grid Square	Equal to a Secondary Area Partition

2. Standard Grid Square Code

The Standard Grid Square Code is defined as follows:

(1) Basic Grid Square Code

Basic Grid Square Code is an 8-digit number. The first 4-digits indicate the Primary Partitions, the next 2-digits indicate the Secondary Partitions, and the last 2-digits indicate the Third Area Partitions.

A. The code indicating the Primary Area Partition is a 4-digit number. The first 2-digits indicate the figure which multiplied the degree of the southernmost latitude of a Partition by 1.5: the first 2-digits are between 30 and 68. The last 2-digits indicate the last 2 digits of the degree of the westernmost longitude of a Partition: the last 2-digits are between 22 and 53.

B. The code indicating the Secondary Area Partition is a 2-digit number. There are 64 (8 by 8) Secondary Area Partitions in one Primary Area Partition. The first 1-digit indicates the number of a Partition which is numbered from the southernmost Partition to the north in a Primary Area Partition, and begins with 0 and ends with 7. The last 1-digit indicates the number of a Partition which is numbered from the westernmost Partition to the east in a Primary Area Partition, and begins with 0 and ends with 7.
That is, the code indicating the Secondary Area Partition is between 00 and 77.

C. The code indicating the Third Area Partition is a 2-digit number. There are 100 (10 by 10) Third Area Partitions in one Secondary Area Partition. The first 1-digit indicates the number of a Partition which is numbered from the southernmost Partition to the north in a Secondary Area Partition, and begins with 0 and ends with 9. The last 1-digit indicates the number of a Partition which is numbered from the westernmost Partition to the east in a Secondary Area Partition, and begins with 0 and ends with 9.
That is, the code indicating the Third Area Partition is between 00 and 99.

(2) Divided Grid Square Code

Divided Grid Square Code is as follows:

A. The code indicating the Half Grid Square is a 9-digit number which consists of the Basic Grid Square Code and one more digit as the ninth digit. There are 4 (2 by 2) Half Grid Squares in a Basic Grid Square. The ninth digit indicates the number of a Half Grid Square which is numbered by the following order: southwest is 1, southeast are 2, northwest is 3, and northeast is 4.

B. The code indicating the Quarter Grid Square is a 10-digit number which consists of the Half Grid Square Code and one more digit as the tenth digit. There are 4 (2 by 2) Quarter Grid Squares in a Half Grid Square. The tenth digit indicates the number of a Quarter Grid

Square which is numbered by the same order as the Half Grid Square: southwest is 1, southeast is 2, northwest is 3, and northeast is 4.

C. The code indicating the Eighth Grid Square is an 11-digit number which consists of the Quarter Grid Square Code and one more digit as the eleventh digit. There are 4 (2 by 2) Eighth Grid Squares in a Quarter Grid Square. The eleventh digit indicates the number of an Eighth Grid Square which is numbered by the same order as the Half Grid Square: southwest is 1, southeast is 2, northwest is 3, and northeast is 4.

(3) Integrated Grid Square Code

Integrated Grid Square Code is as follows:

A. The code indicating the Double Grid Square is a 9-digit number which consists of the first 6-digits of the Basic Grid Square Code and three more digits as the seventh to ninth digits. There are 16 (4 by 4) Double Grid Squares in a Secondary Area Partition. The seventh digit indicates the number of a Double Grid Square which is numbered by the following order: 0,2,4,6 and 8 from the southernmost Square to the north in a Secondary Area Partition. The eighth digit indicates the number of a Double Grid Square which is numbered by the following order: 0,2,4,6 and 8 from the westernmost Square to the east in a Secondary Area Partition. The ninth digit is 5.

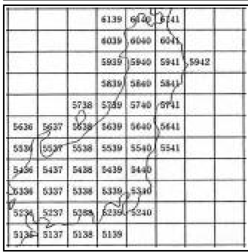
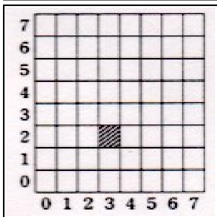
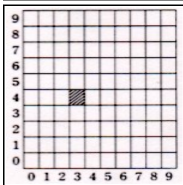
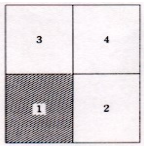
B. The code indicating the Quintuple Grid Square is a 7-digit number which consists of the first 6-digits of the Basic Grid Square Code and one more digit as the seventh digit. There are 4 (2 by 2) Quintuple Grid Squares in a Secondary Area Partition. The seventh digit indicates the number of a Quintuple Grid Square which is numbered by the following order: southwest is 1, southeast are 2, northwest are 3, and northeast are 4.

C. The code indicating the Decuple Grid Square is a 6-digit number which is the same code as the first 6-digits of the Basic Grid Square Code.

(4) Partially Omitted Code

When you use the Standard Grid Square Code, the upper digits of the code can be omitted. In this case, you need to clarify where the shortened code should be located in the Standard Grid Square Code.

Chart for Method of Demarcation

	Divide a Primary Area Partition into 64 (8 by 8) equal parts vertically and horizontally:	Divide a Secondary Area Partition into 100 (10 by 10) equal parts vertically and horizontally:	Divide a Basic Grid Square into 4 (2 by 2) equal parts vertically and horizontally:
Primary Area Partition	**Secondary Area Partition**	**Third Area Partition (Basic Grid Square)**	**Divided Grid Square (Half Grid Square)**
The Primary Area Partition including Metropolitan Tokyo is:	The screened Secondary Area Partition is:	The screened Third Area Partition is:	The screened Divided Grid Square is:
Mesh code: 5339	5339-23	5339-23-43	5339-23-43-1
			

Appendix B

APPENDIX B-1

The Amount of Debris in Every Node (in Ton)

1/46/A/B/C = 0; 2 = 81.1; 3 = 83.5; 4 = 21.1; 5 = 65.9; 6 = 65.9; 7 = 84.6; 8 = 1.8; 9 = 94.4; 10 = 83.5; 11 = 70.3; 12 = 49.2; 13 = 59.3; 14 = 94.4; 15 = 44.8; 16 = 91.6; 17 = 1.4;18 = 1.4;19 = 8.6; 20 = 99.6; 21 = 81.1; 22 = 99.6; 23 = 36.5; 24 = 79.2; 25 = 70.3; 26 = 21.1; 27 = 27.5; 28 = 44.6; 29 = 26.2; 30 = 27.5; 31 = 59.3; 32 = 98.5; 33 = 24.2; 34 = 24.2; 35 = 44.6; 36 = 26.2; 37 = 84.6; 38 = 1.8; 39 = 44.8; 40 = 91.6;41 = 8.6; 42 = 36.5; 43 = 79.2; 44 = 49.2; 45 = 98.5

APPENDIX B-2

The Best Route of Vehicles

1-3-10-46-4-26-29-36-27-30-33-34-46-2-21-19-41-18-17-46-5-6-8-38-46-7-37-46-9-14-46-11-25-46-12-44-28-35-46-13-31-46-20-22-46-23-42-15-39-46-16-40-46-24-43-46-32-45-1

Appendix C

APPENDIX C-1

The Amount of Debris in Every Node (in Ton)

1/198/199/A/B/C = 0; 2 = 23.7; 3 = 23.7; 4 = 30.7; 5 = 30.7; 6 = 11.3; 7 = 11.3; 8 = 18.4; 9 = 18.4; 10 = 42.1; 11 = 42.1; 12 = 46; 13 = 46; 14 = 92.2; 15 = 92.2; 16 = 60.8; 17 = 60.8; 18 = 64.8; 19 = 64.8; 20 = 21.1; 21 = 21.1; 22 = 20.9; 23 = 20.9; 24 = 21; 25 = 21; 26 = 29.3; 27 = 29.3; 28 = 23.7; 29 = 23.7; 30 = 18.6; 31 = 18.6; 32 = 22.1; 33 = 22.1; 34 = 41.5; 35 = 1.5; 36 = 55.2; 37 = 55.2; 38 = 21.7; 39 = 21.7; 40 = 23.6; 41 = 23.6; 42 = 46.3; 43 = 46.3; 44 = 35.7; 45 = 35.7; 46 = 22.9; 47 = 22.9; 48 = 21.6; 49 = 21.6; 50 = 23.7; 51 = 23.7; 52 = 20; 53 = 20; 54 = 21.4; 55 = 21.4; 56 = 15.5; 57 = 15.5; 58 = 10.1; 59 = 10.1; 60 = 15.4; 61 = 15.4; 62 = 16.3; 63 = 16.3; 64 = 11.3; 65 = 11.3; 66 = 31.3; 67 = 31.3; 68 = 19; 69 = 19; 70 = 23.4; 71 = 23.4; 72 = 22.7; 73 = 22.7; 74 = 14.6; 75 = 14.6; 76 = 40.9; 77 = 40.9; 78 = 9.4; 79 = 9.4; 80 = 12.3; 81 = 12.3; 82 = 21.7; 83 = 21.7; 84 = 22.8; 85 = 22.8; 86 = 14.5; 87 = 14.5; 88 = 9.4; 89 = 9.4; 90 = 11.9; 91 = 11.9; 92 = 15.1; 93 = 15.1; 94 = 14.6; 95 = 14.6; 96 = 12.3; 97 = 12.3; 98 = 9.7; 99 = 9.7; 100 = 11.8; 101 = 1.8; 102 = 7.3; 103 = 7.3; 104 = 19.6; 105 = 19.6; 106 = 17.2; 107 = 17.2; 108 = 14.9; 109 = 14.9; 110 = 13.8; 111 = 13.8; 112 = 8.7; 113 = 8.7; 114 = 12.9; 115 = 12.9; 116 = 13.8; 117 = 13.8; 118 = 10.8; 119 = 10.8; 120 = 8.1; 121 = 8.1; 122 = 8.7; 123 = 8.7; 124 = 6.8; 125 = 6.8; 126 = 15.7; 127 = 15.7; 128 = 14.7; 129 = 14.7; 130 = 12.9; 131 = 12.9; 132 = 14.9; 133 = 14.9; 134 = 11.1; 135 = 11.1; 136 = 7.5; 137 = 7.5; 138 = 10.7; 139 = 10.7; 140 = 12.6; 141 = 12.6; 142 = 9.3; 143 = 9.3; 144 = 7.8; 145 =

7.8; 146 = 6.8; 147 = 6.8; 148 = 5.1; 149 = 5.1; 150 = 6.9; 151 = 6.9; 152 = 18.8; 153 = 18.8; 154 = 9.5; 155 = 19.5; 156 = 16; 157 = 16; 158 = 38; 159 = 38; 160 = 31.1; 161 = 31.1; 162 = 23.1; 163 = 3.1; 164 = 17.7; 165 = 17.7; 166 = 43.6; 167 = 43.6; 168 = 41.1; 169 = 41.1; 170 = 15.5; 171 = 15.5; 172 = 8.8; 173 = 8.8; 174 = 53.7; 175 = 53.7; 176 = 24.7; 177 = 24.7; 178 = 15.9; 179 = 15.9; 180 = 6.6; 181 = 56.6; 182 = 19.1; 183 = 19.1; 184 = 34.9; 185 = 34.9; 186 = 77.7; 187 = 77.7; 188 = 67.5; 189 = 67.5; 190 = 94.3; 191 = 94.3; 192 = 6.3; 193 = 6.3; 194 = 39.6; 195 = 39.6; 196 = 7.3; 197 = 7.3

APPENDIX C-2

The Best Route of Vehicles

1-182-183-180-181-179-178-198-188-189-196-197-193-192-173-172-198-184-185-105-104-103-102-129-128-121-120-99-98-198-169-168-145-144-141-140-115-114-113-112-80-81-198-171-170-78-79-162-163-158-159-148-149-150-151-198-177-176-174-175-164-165-198-166-167-143-142-139-138-137-136-131-130-119-118-198-186-187-101-100-89-88-198-106-107-108-109-97-96-83-82-75-74-57-56-198-127-126-125-124-117-116-111-110-84-85-86-87-91-90-198-67-66-55-54-31-30-28-29-198-155-154-13-12-9-8-122-123-146-147-198-157-156-161-160-152-153-132-133-134-135-198-194-195-25-24-3-2-58-59-198-93-92-63-62-49-48-47-46-73-72-198-65-64-53-52-51-50-32-33-68-69-198-77-76-41-40-39-38-198-191-190-198-70-71-61-60-94-95-43-42-198-27-26-5-4-20-21-198-34-35-36-37-198-22-23-19-18-7-6-198-45-44-17-16-198-11-10-198-14-15-1

APPENDIX C-3

The Best Route of Vehicles

1-184-185-105-104-103-102-129-128-121-120-99-98-199-45-44-17-16-199-46-47-60-61-71-70-63-62-49-48-199-43-42-41-40-39-38-199-56-57-73-72-94-95-83-82-75-74-173-172-198-188-189-193-192-196-197-171-170-198-182-183-177-176-174-175-198-169-168-145-144-141-140-142-143-149-148-150-151-147-146-137-136-199-81-80-111-110-97-96-84-85-86-87-88-89-100-101-198-178-179-180-181-79-78-164-165-198-166-167-152-153-132-133-134-135-138-139-199-35-34-32-33-27-26-199-36-37-154-155-157-156-122-123-199-51-50-52-53-31-30-28-29-58-59-199-112-113-77-76-13-12-199-116-117-124-125-119-118-109-108-107-106-67-66-199-114-115-126-127-130-131-93-92-69-68-65-64-90-91-199-54-55-25-24-3-2-21-20-7-6-199-15-14-199-18-19-5-4-199-190-191-198-162-163-158-159-161-160-198-186-187-22-23-199-9-8-11-10-199-194-195-1

APPENDIX C-4

The Best Route of Vehicles

Group_1 = 1-188-189-193-192-198-178-179-180-181-198-105-104-198-129-128-121-120-199-43-42-199-48-49-199-74-75-122-123-199-71-70-199-62-63-124-125-199-76-77-137-136-199-92-93-199-54-55-199-39-38-199-130-131-135-134-199-15-14-199-190-191-198-194-195-1

Group_2 = 1-173-172-169-168-198-177-176-198-166-167-198-158-159-161-160-198-106-107-67-66-199-60-61-89-88-199-81-80-112-113-199-52-53-199-116-117-139-138-199-114-115-146-147-199-31-30-27-26-199-86-87-5-4-199-28-29-199-18-19-199-132-133-199-20-21-1

Group_3 = 1-184-185-186-187-196-197-198-164-165-174-175-198-103-102-101-100-199-46-47-199-56-57-36-37-199-35-34-150-151-199-51-50-199-111-110-118-119-199-96-97-140-141-198-127-126-199-64-65-90-91-199-13-12-199-7-6-199-25-24-199-9-8-199-3-2-1

Group_4 = 1-182-183-198-171-170-78-79-198-162-163-198-145-144-148-149-143-142-199-45-44-17-16-199-73-72-199-82-83-199-94-95-99-98-199-41-40-199-84-85-199-69-68-199-109-108-59-58-199-32-33-199-154-155-198-157-156-198-152-153-199-11-10-199-22-23-1

Appendix D

APPENDIX D-1

The Best Route of Vehicles

1/A-3-10-A-2-21-19-41-18-17-A-4-26-29-36-27-30-33-34-A-5-6-8-38-A-7-37-A-9-14-A-11-25-A-12-44-23-42-A-13-31-A-20-22-A-28-35-15-39-A-16-40-A-24-43-A-32-45-1/A

Appendix E

APPENDIX E-1

The Best Route of Vehicles

1/A-62-63-69-68-65-64-31-30-27-26-A-49-48-47-46-43-42-A-51-50-32-33-28-29-58-59-53-52-A-70-71-61-60-72-73-57-56-74-75-A-92-93-85-84-83-82-81-80-111-110-97-96-A-54-55-66-67-89-88-100-101-102-103-129-128-A-34-35-36-37-A-86-87-91-90-98-99-107-106-104-105-121-120-108-109-A-94-95-118-119-125-124-117-116-112-113-77-76-A-45-44-17-16-A-127-126-130-131-135-134-132-133-153-152-147-146-137-136-138-139-A-25-24-3-2-21-20-5-4-A-190-191-A-19-18-7-6-22-23-A-41-40-39-38-13-12-151-150-A-123-122-115-114-140-141-144-145-167-166-78-79-A-142-143-149-148-168-169-171-170-164-165-172-173-A-185-184-182-183-177-176-179-178-A-186-187-192-193-196-197-A-15-14-A-154-155-157-156-159-158-163-162-A-188-189-161-160-A-9-8-11-10-A-180-181-194-195-A-174-175-1/A

APPENDIX E-2

The Best Route of Vehicles

1/A-62-63-69-68-65-64-31-30-27-26-A-49-48-47-46-43-42-A-52-53-54-55-59-58-29-28-33-32-A-51-50-34-35-56-57-74-75-A-70-71-61-60-72-73-81-80-111-110-97-96-A-92-93-98-99-107-106-101-100-67-66-89-88-A-85-84-83-82-112-113-77-76-A-86-87-91-90-102-103-104-

105-185-184-173-172-C-177-176-79-78-164-165-158-159-120-121-A-94-95-109-108-127-126-119-118-125-124-117-116-114-115-122-123-A-45-44-17-16-A-128-129-186-187-192-193-B-191-190-A-25-24-22-23-3-2-21-20-7-6-A-36-37-39-38-154-155-C-179-178-169-168-145-144-141-140-139-138-137-136-A-130-131-135-134-132-133-153-152-147-146-151-150-143-142-149-148-196-197-B-189-188-182-183-C-180-181-171-170-162-163-C-174-175-166-167-C-157-156-161-160-13-12-A-5-4-19-18-A-41-40-9-8-11-10-A-15-14-A-194-195-1/A

APPENDIX E-3

The Best Route of Vehicles

Group_1 = 1/A-52-53-A-69-68-A-60-61-120-121-A-34-35-36-37-A-43-42-A-107-106-102-103-A-96-97-118-119-A-190-191-187-186-C-179-178-172-173-C-183-182-174-175-C-162-163-C-164-165-150-151-C-158-159-161-160-C-155-154-A-132-133-A-13-12-1/A

Group_2 = 1/A-49-48-A-70-71-A-31-30-27-26-A-85-84-A-94-95-67-66-A-108-109-59-58-A-127-126-125-124-A-110-111-112-113-A-19-18-142-143-C-177-176-C-79-78-184-185-149-148-C-166-167-C-141-140-146-147-C-157-156-C-152-153-A-9-8-1/A

Group_3 = 1/A-51-50-A-92-93-98-99-A-64-65-90-91-A-72-73-A-45-44-17-16-A-28-29-A-128-129-A-100-101-130-131-A-104-105-C-180-181-169-168-C-171-170-145-144-C-188-189-193-192-B-194-195-196-197-B-22-23-A-39-38-A-15-14-1/A

Group_4 = 1/A-62-63-A-47-46-A-54-55-A-32-33-A-86-87-88-89-A-56-57-5-4-A-83-82-A-74-75-A-25-24-A-81-80-123-122-A-20-21-A-116-117-139-138-A-41-40-A-76-77-137-136-A-3-2-A-135-134-115-114-A-7-6-A-11-10-1/A